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Pressurized Slot Testing to Determine Thermo-Mechanical Properties of Lithophysal Tuff at Yucca Mountain, Nevada

James T. George, Moo Y. Lee, Steven R. Sobolik, Byoung Y. Park, and Laurence S. Costin

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Pressurized Slot Testing to Determine Thermo-Mechanical Properties of Lithophysal Tuff at Yucca Mountain, Nevada

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Abstract

The study described in this report involves heated and unheated pressurized slot testing to determine thermo-mechanical properties of the Tptpll (Tertiary, Paintbrush, Topopah Spring Tuff Formation, crystal poor, lower lithophysal) and Tptpul (upper lithophysal) lithostratigraphic units at Yucca Mountain, Nevada. A large volume fraction of the proposed repository at Yucca Mountain may reside in the Tptpll lithostratigraphic unit. This unit is characterized by voids, or lithophysae, which range in size from centimeters to meters, making a field program an effective method of measuring bulk thermal-mechanical rock properties (thermal expansion, rock mass modulus, compressive strength, time-dependent deformation) over a range of temperature and rock conditions. The field tests outlined in this report provide data for the determination of thermo-mechanical properties of this unit. Rock-mass response data collected during this field test will reduce the uncertainty in key thermal-mechanical modeling parameters (rock-mass modulus, strength and thermal expansion) for the Tptpll lithostratigraphic unit, and provide a basis for understanding thermal-mechanical behavior of this unit. The measurements will be used to evaluate numerical models of the thermal-mechanical response of the repository. These numerical models are then used to predict pre- and post-closure repository response.

ACKNOWLEDGEMENTS

The authors would like to thank David Bronowski, Ronnie Taylor, Ray E. Finley, Cliff Howard, Michael Schuhen (all SNL) and Fred Homuth (LANL) for their work in the planning and implementation of the tests described in this report.

This is a reprint of SAND2004-2703, which was originally printed in July 2004. At that time, it was printed for a restricted audience. It has now been approved for unlimited release.

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1. INTRODUCTION

The welded tuffs of Yucca Mountain, Nevada are being considered by the United States Department of Energy (DOE) as potential host media for the storage of high level radioactive waste. The geological stratigraphy at Yucca Mountain, shown in Figure 1, contains alternating layers of welded and non-welded tuffs, with alternating qualities of fractures and lithophysae. As part of the site characterization efforts for the Yucca Mountain Project (YMP), a mechanically excavated Exploratory Studies Facility (ESF) was completed in 1997. Most of the ESF is contained in the Tptpmn (Tertiary, Paintbrush, Topopah Spring Tuff Formation, crystal poor, middle non-lithophysal) lithostratigraphic unit, with the ramps of the drift primarily in the Tptpul (Tertiary, Paintbrush, Topopah Spring Tuff Formation, crystal poor, upper lithophysal) unit. In 2000, an additional drift was excavated from the ESF into the Tptpll (Tertiary, Paintbrush, Topopah Spring Tuff Formation, crystal poor, lower lithophysal) lithostratigraphic unit beneath the ESF, where most of the proposed repository is expected to be constructed; this drift is known as the Enhanced Characterization of the Repository Block (ECRB) Drift. The plan view layout of the ESF and ECRB drifts is shown in Figure 2. Several underground in situ tests have been performed in the ESF and ECRB since their construction. The goal of these tests was to evaluate components of the coupled thermal-mechanical-hydrologic-chemical (T-M-H-C) response of the repository host rock to elevated temperatures representative of a high level nuclear waste repository.

This report details a series of heated and unheated pressurized slot tests performed in three locations in the ESF and ECRB. Three separate pressurized slot tests were performed; the locations and details of these tests are summarized in Table 1. These tests were designed to determine thermo-mechanical properties of the Tptpll lithostratigraphic unit. A large volume fraction of the proposed repository at Yucca Mountain may reside in the Tptpll lithostratigraphic unit. This unit is characterized by voids, or lithophysae, which range in size from centimeters to meters, making a field program an effective method of measuring bulk thermal-mechanical rock properties (thermal expansion, rock mass modulus, compressive strength, time-dependent deformation) over a range of temperature and rock conditions. The field tests outlined in this report have provided data for the determination of thermo-mechanical properties of this unit.

Table 1. Summary of Pressurized Slot Tests

Test No.	Dates of Test	Test Location	Type of Test
1	5/8/2002	Exploratory Studies Facility Station 57+77, in the Tptpll unit	Ambient; rib placement
2	10/15/2002-10/30/2002	Exploratory Studies Facility Station 63+83, in the Tptpul unit	Ambient and heated; rib placement
3	12/10/2002	ECRB Station 21+25, in the Tptpll unit	Ambient; invert placement

Rock-mass response data collected during these field tests will reduce the uncertainty in key thermal-mechanical modeling parameters (rock-mass modulus, strength and thermal expansion) for the Tptpll lithostratigraphic unit, and provide a basis for understanding thermal-mechanical behavior of this unit. These measurements will be used to evaluate numerical models of the thermal-mechanical response of the repository that are then used to predict pre- and post-closure repository response.

The pressurized slot tests were performed in full compliance with the Yucca Mountain Quality Assurance (QA) and Integrated Safety Management (ISM) requirements. The products from these tests support the resolution of Key Technical Issues (KTIs) (Pannell 2001) associated with the Repository Design and Thermal-Mechanical Effects (RDTME). The KTIs are issues identified by the Nuclear Regulatory Commission and communicated to the Office of Civilian Radioactive Waste Management during their reviews of the scientific program. The data acquired from this study support the following KTIs :

RDTME 3.4 - Provide site specific properties of the host rock.
RDTME 3.5 - Provide Rock Mass Classification Analysis and account for lithophysae,
RDTME 3.6 - Provide the design sensitivity and uncertainty analysis of the rock support system.
RDTME 3.7 - Account for the effect of sustained load on intact rock strength.
RDTME 3.11 - Provide continuum and discontinuum analyses of ground support system performance.
RDTME 3.15 - Provide field data and analysis of rock bridges between rock joints.
RDTME 3.16 - Provide a technical basis for the method used to model joint planes.
RDTME 3.19 - Determine whether rockfall can be screened out from performance assessment abstractions.
RDTME 3.20 - Provide sensitivity analysis of thermal mechanical effects on fracture permeability.
RDTME 3.21 - Provide results of field tests related to thermal mechanical effects on fracture permeability.

In addition, the data will support revisions to the *Drift Degradation Analysis and Model Report* (AMR) (CRWMS M&O 1999) and the *Coupled Thermal-Hydrologic-Mechanical Effects on Permeability AMR* (BSC 2001). The primary products of this work were thermal and mechanical property data that were submitted to the Technical Data Management System (TDMS).

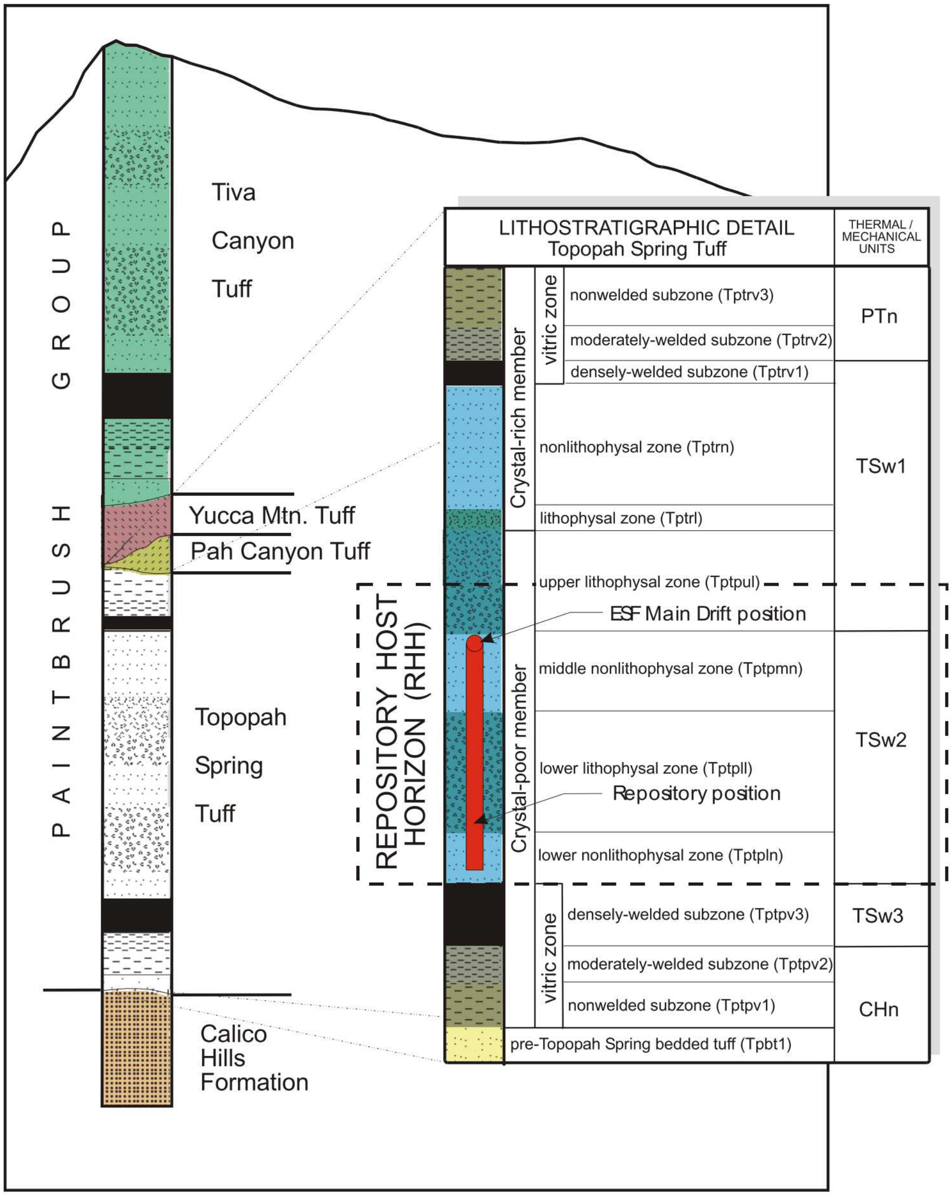


Figure 1. Stratigraphy at Yucca Mountain, Nevada

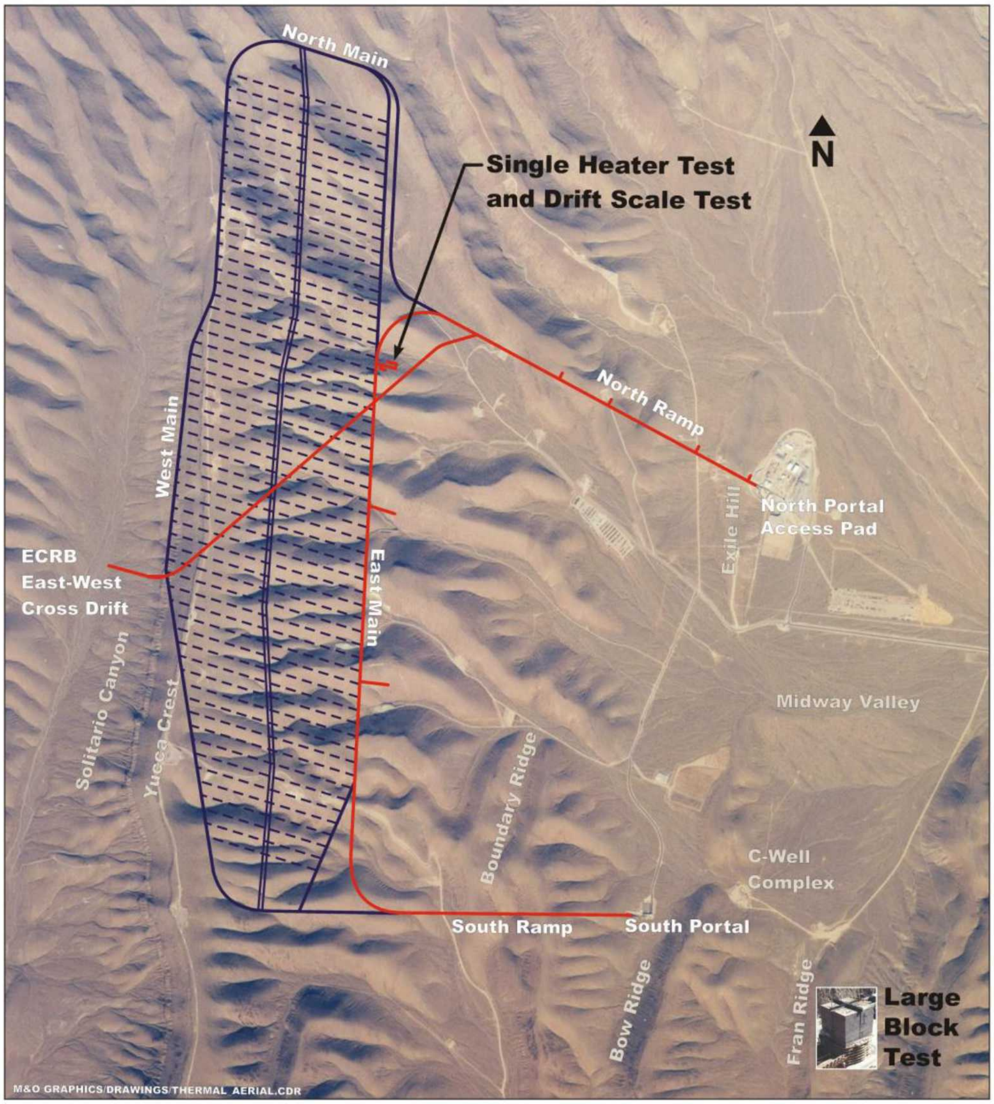


Figure 2. Layout of ESF and ECRB at Yucca Mountain.

2. TEST DESIGN

The pressurized slot testing described in this report has provided thermal-mechanical properties of the Tptpll lithostratigraphic unit. At the selected test locations, the rib and/or invert surfaces were instrumented to monitor deformation as two slots were cut to create a "tendon" of rock between them. Manual displacement measurements were made prior to and after slot cutting to provide the complete deformation history for the rock mass surrounding the slot. Flat jacks and bearing platens were placed in the slots, which were instrumented to measure displacement across the slot. During the initial flat jack pressurization, the pressure at which the deformation of the rock cancelled the deformation due to slot cutting was used to estimate the in situ stress acting normal to the slots. Subsequent loading-unloading cycles provided a pressure/ deformation history that was evaluated to determine the rock mass deformation modulus. Additional information was obtained by including a borehole in the center of the tendon between the slots and measuring the deformation across the borehole diameter as the slots were loaded. As the pressures in the flat jacks increased, the stress around the borehole also increased, in some cases resulting in failure of the rock. The failure stress of the rock was then determined from the borehole observations and modeling of the behavior. Information regarding the thermal expansion of the rock mass was obtained by heating the rock tendon with resistive heaters placed in drill holes and monitoring the deformations in the central borehole and slots prior to pressurization. The influence of elevated temperature on thermal mechanical properties was evaluated by loading-unloading the rock in a manner similar to that done under ambient temperatures. Finally, the rock mass strength was evaluated by increasing the flat jack pressure until gross failure of the tendon of rock between the flat jacks occurred. Because these tests were conducted in a complex configuration, numerical modeling of each test was required during both test design and for post-test analyses of the results. Scoping calculations are described in Section 3, and post-test analyses are described in many of the succeeding sections.

Multiple field tests were planned to allow an integration of a range of responses for various conditions in the unit, including lithophysae size and joint frequency (see Table 1 for a summary of the tests). The first test was conducted at ambient temperatures in a location within the ESF South Ramp, in the Tptpll unit. The second test was conducted in the ESF South Ramp in the Tptpul lithographic unit, which is very similar in nature to the Tptpll unit. The second test also included both ambient and heated phases. The third test was located at a location within the Enhanced Characterization Repository Block (ECRB) Cross Drift, in the Tptpll unit.

This section gives detailed information of the test design and procedure. Sections 4, 5, and 6 will report the specific dimensions and procedure for each of three tests, and the post-test analyses used to determine rock-mass mechanical properties from each test.

2.1 SLOT TEST DESIGN SPECIFICS

2.1.1 Test layout

The design test layout for the three slot tests described in Table 1 is shown in Figure 3. The dimensions given in this section are nominal design dimensions; the as-built dimensions are given in Sections 4, 5, and 6. A tendon of rock nominally 122 cm wide was created by cutting two vertical slots in the rib or the invert. The slots were nominally 3.8 cm wide, 122 cm deep and extended to a height of 214 cm above the pre-cast invert for the rib tests. Flat jacks with integral bearing platens for loading the rock tendon were placed in the slots. A 30.5-cm diameter, 122-cm deep borehole was centrally located between the slots, and was used to measure rock deformation. For the slot tests #2 and #3, two series of 7.6-cm diameter holes were located above and below the central 30.5-cm diameter borehole. These boreholes were designed to accommodate heaters; electrical heaters were used for slot test #2, but were not used for slot test #3 based on the results of the previous test. The test sites were selected by representatives of Sandia National Laboratories (SNL) and the Los Alamos National Laboratory (LANL) Test Coordination Office (TCO).

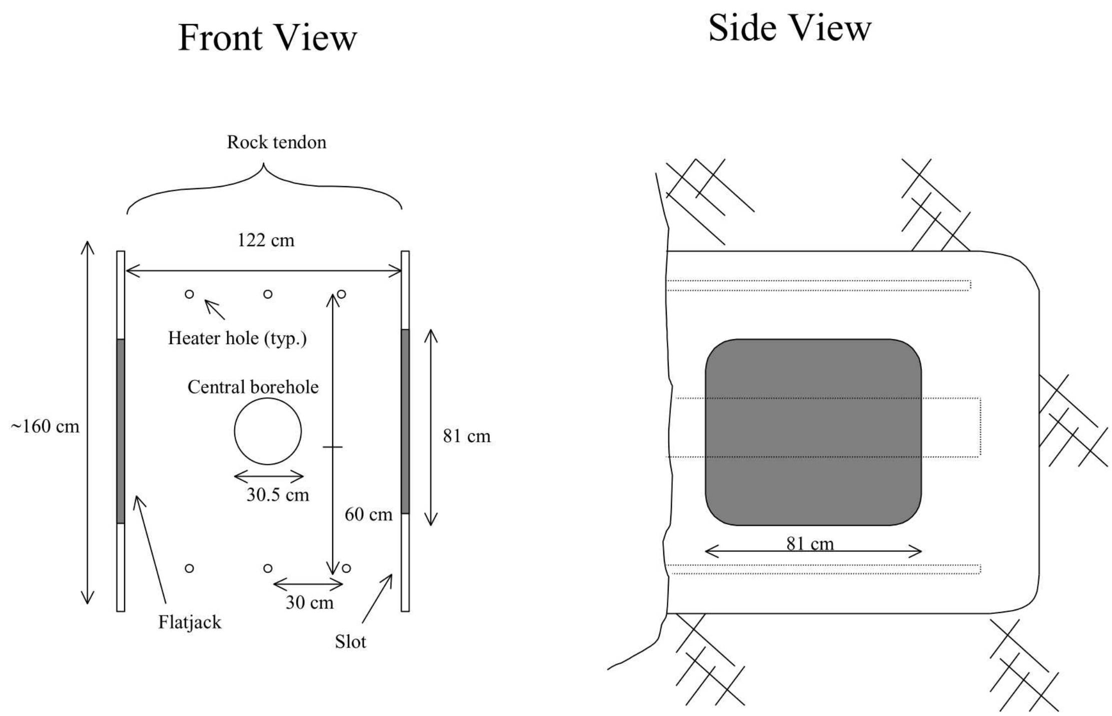


Figure 3. Pressurized slot test layout.

2.1.2 Rock surface displacement

Deformations on the rib surface were measured between metallic dowel pins that were set into the rock a minimum depth of 15 cm. Pin locations were based on geometric considerations set by the central hole and slot geometries. These pins were used to measure horizontal deformation across the slots and across the tendon at three elevations. Pins were also used to measure vertical deformation across the central hole and tendon. The locations of these pins are given in Figure 4.

Prior to and immediately after cessation of sawing, manual measurements between the metallic dowels were made to determine baseline readings indicative of closure or relaxation of the slot as a result of the sawing activity. These baseline measurements were taken to provide a complete pre-test deformation history for the rock mass surrounding the slot. Prior to flat jack pressurization, stranded stainless steel measurement wires and rotating linear potentiometer gages, a.k.a. "yo-yo" gages were installed to automatically measure subsequent deformations.

The locations of the surface deformation gages are given in Table 2. The origin of the coordinate system is the intersection of the rib and centerline of the central borehole. The y coordinate is along the borehole axis, z coordinate is vertical, and *x* is horizontal to the right in Figure 4. The photograph in Figure 5 shows the installation of the dowels and gages outlined in Figure 4.

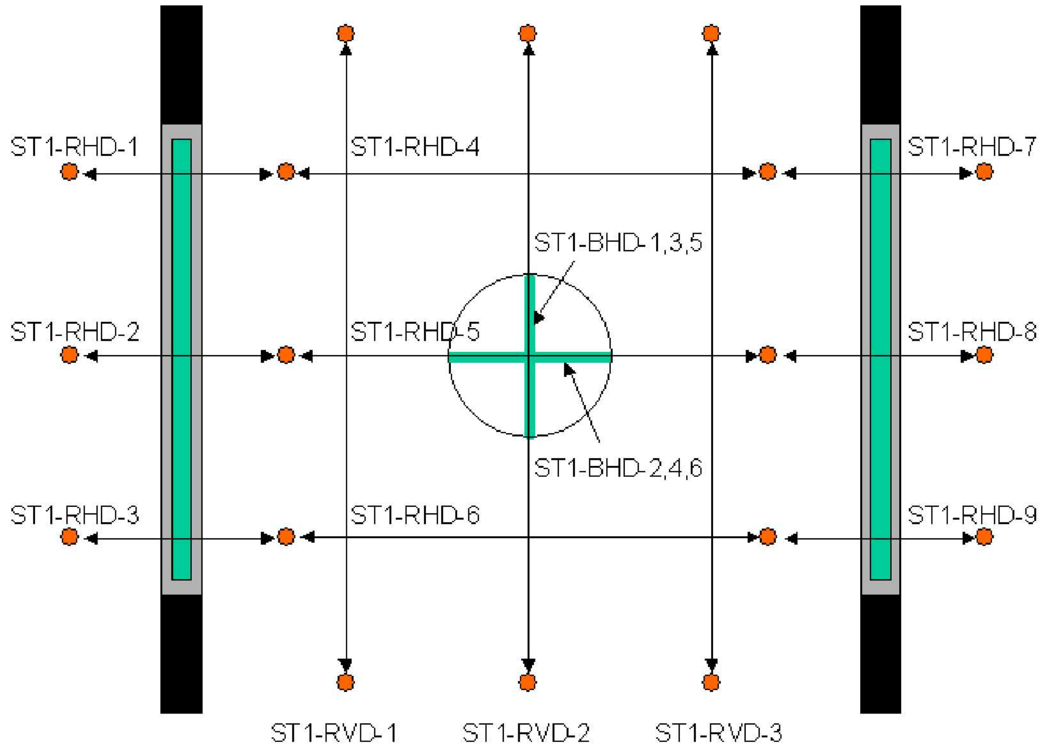


Figure 4. Surface deformation measurement locations.

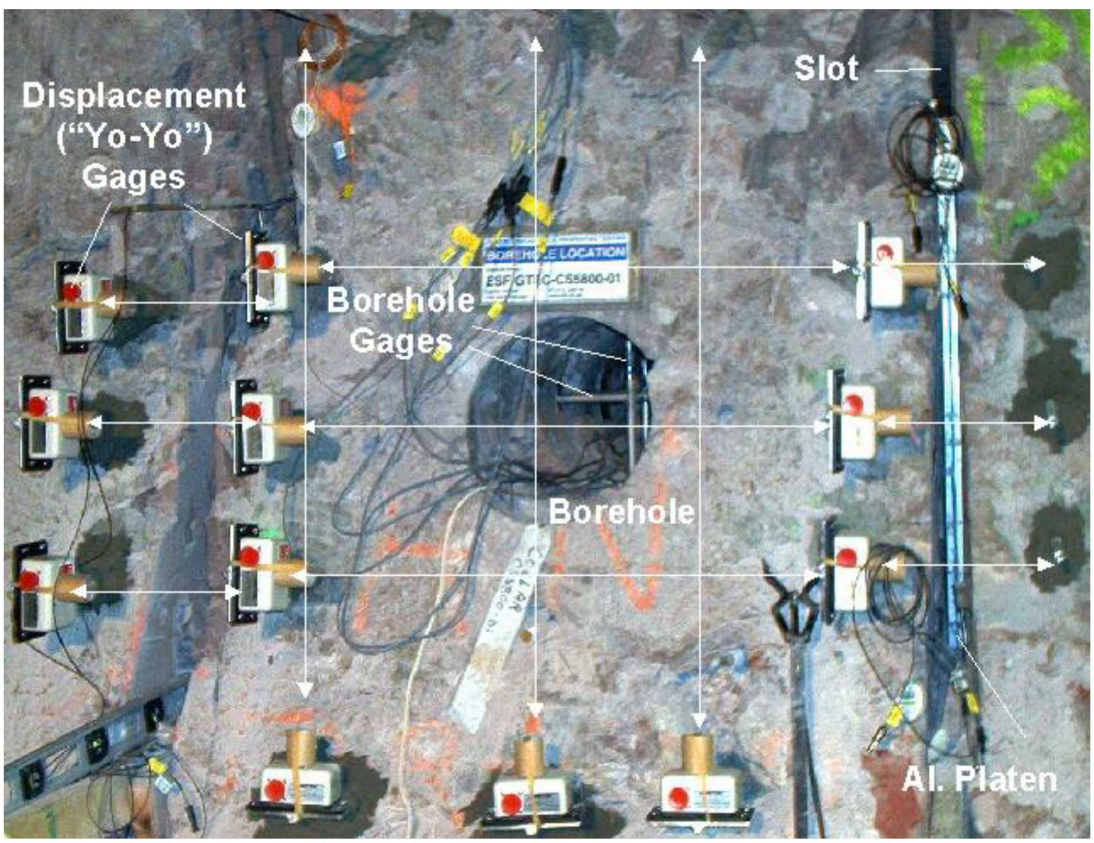


Figure 5. Surface deformation measurement as-built locations.

Table 2. Locations of surface displacement gages (all distances in cm).

Gage number *	x1	x2	y1	y2	z1	z2	Sensing direction
ST*n*-RHD-1	-91.5	-30.5	0	0	30.5	30.5	Horizontal
ST*n*-RHD-2	-91.5	-30.5	0	0	0	0	Horizontal
ST*n*-RHD-3	-91.5	-30.5	0	0	-30.5	-30.5	Horizontal
ST*n*-RHD-4	-30.5	30.5	0	0	30.5	30.5	Horizontal
ST*n*-RHD-5	-30.5	30.5	0	0	0	0	Horizontal
ST*n*-RHD-6	-30.5	30.5	0	0	-30.5	-30.5	Horizontal
ST*n*-RHD-7	30.5	91.5	0	0	30.5	30.5	Horizontal
ST*n*-RHD-8	30.5	91.5	0	0	0	0	Horizontal
ST*n*-RHD-9	30.5	91.5	0	0	-30.5	-30.5	Horizontal
ST*n*-RVD-1	-30.5	-30.5	0	0	60.5	-60.5	Vertical
ST*n*-RVD-2	0	0	0	0	60.5	-60.5	Vertical
ST*n*-RVD-3	30.5	30.5	0	0	60.5	-60.5	Vertical

* - Where *n* is the specific test number.

Table 3. Locations of central borehole displacement gages (all distances in cm).

Gage number *	x1	x2	y1	Y2	z1	z2	Sensing direction
ST*n*-BH-1	15.25	-15.25	30.5	30.5	0	0	horizontal
ST*n*-BH-2	0	0	30.5	30.5	-15.25	15.25	vertical
ST*n*-BH-3	15.25	-15.25	61	61	0	0	horizontal
ST*n*-BH-4	0	0	61	61	-15.25	15.25	vertical
ST*n*-BH-5	15.25	-15.25	91.5	91.5	0	0	horizontal
ST*n*-BH-6	0	0	91.5	91.5	-15.25	15.25	vertical

* - Where *n* is the specific test number.

2.1.3 Hole drilling

The central hole was drilled horizontally at a nominal distance of 60 cm above the invert for slot tests #1 and #2; for slot test #3, the central hole was drilled vertically in the middle of the floor of the ECRB. The hole diameter was 30.5 cm, and the hole was designed to extend at least 122 cm into the host rock.

There were two rows of heater holes, one row located above and the other row below the central hole. Within each row, there were three evenly spaced heater drill holes. The heater holes were nominally horizontal, 2.54 cm in diameter and a minimum of 204 cm in depth. The number and placement of the heater holes were determined by the pre-test scoping calculations. The initial test in the South Ramp at the 57+77 location did not include heater boreholes.

2.1.4 Central borehole displacement

Six 'captured plunger' gages employing cantilevered strain gages were used within the central 30.5-cm diameter hole centered between the cut slots. The gages were located approximately at the quarter points along the axis of the hole both in the horizontal and vertical directions, allowing for variations due to rock quality in the borehole. To facilitate gage placement within the 30.5-cm diameter borehole, a series of lightweight bearing platens were fabricated to maintain instrument position and provide adequate bearing surfaces. The locations of these gages are described in Table 3.

2.1.5 Slot cutting

The slots were cut with the SNL hydraulic rock saw system (HRSS), which is a diamond abrasive belt saw, hydraulically powered and controlled, and mounted in a specially designed frame. ESF construction personnel under the guidance of the SNL, assembled, operated and cut two slots for each test. A photo of the HRSS is shown in Figure 6. For the first two tests, vertical slots were cut into the rib of the drift. For test #3, the test was re-designed, with the slots and boreholes cut into the invert of the ECRB.

Figure 6. Photo of HRSS Cutting Slot 1A, Pressurized Slot Test 2.

2.1.6 Slot Deformation

Miniature rotating linear potentiometric ('yo-yo') gages, with a 0 to 5 cm range, were located within the loading platens. Measurements between the two load bearing platens (normal to the sawn slots) were facilitated using a system of small pulleys internal to the load bearing platens. A total of eight (8) gages (one at each corner of the platen assemblies) measured the displacements. These slot deformation gages are listed in Table 4.

Table 4. Position of slot deformation gages (all distances in cm).

Gage number *	x	y**	z	Sensing direction
ST*n*-LPD-1	61	67	45.5	horizontal
ST*n*-LPD-2	61	67	-45.5	horizontal
ST*n*-LPD-3	61	158	45.5	horizontal
ST*n*-LPD-4	61	158	-45.5	horizontal
ST*n*-RPD-1	-61	67	45.5	horizontal
ST*n*-RPD-2	-61	67	-45.5	horizontal
ST*n*-RPD-3	-61	158	45.5	horizontal
ST*n*-RPD-4	-61	158	-45.5	horizontal

* - Where *n* is the specific test number.

** - y refers to distance from the front edge of the bearing platen to the drift wall

2.1.7 Other instrumentation and data acquisition

Pressure transducers were used to monitor the flat jack system pressure. Excitation power for the rotating linear potentiometers, captured plunger gages, and the pressure transducers was provided by an SNL-owned power supply with a rated output of 0-30 Vdc. A Fluke Model 743 B calibrator was used to provide a calibrated 0-10 Vdc signal to the Data Acquisition System terminal board both before and after the conduct of the pressurized slot tests. All of this equipment has been used in previous Plate Loading Tests conducted in the ESF, and have been calibrated per YMP QA requirements.

A data collection system (DCS) was configured by the TCO to record all gage outputs at time intervals determined by rate and magnitude of displacements observed during previous testing activities using similar flat jack designs.

The displacements (rib surface, slot and central borehole), temperatures and flat jack pressures were typically gathered and archived ten times per second. The rock mass modulus was determined by comparison of data with post-test numerical simulations. The modulus input to the simulations was varied to achieve a "best fit" to the data, thus deriving a rock mass modulus for the test location and conditions. Rock strength was evaluated by determining the approximate stress state (from numerical simulation) at failure locations.

2.1.8 Test procedure for ambient temperature slot tests

The installation and conduct of the ambient temperature slot tests (Tests #1 and #3) involved the following general steps as outlined in the *Test Plan For: Rock Modulus Testing* by George and Howard, 2002, although somewhat modified to accommodate field conditions and test schedule.

1. Site preparation
   A. Mount surface deformation gages - once the surface deformation gages are installed, they should be monitored during subsequent hole drilling.
   B. Core 30.5 cm central hole and inspect hole (map location of lithophysae)

C. Instrument central hole
D. Drill 7.6 cm heater holes

2. Slot cutting and flat jack installation
   (Central hole and surface deformations should be monitored during slot cutting.)
   A. Cut slots with HRSS
   B. Map surface of slots
   C. Install flat jacks and shims along with yo-yo gages
   D. Install instrumentation to remotely measure pin deformations

3. Slot pressurization
   (During this portion of test, all instrumentation should be monitored. In addition, observations should be made of any spalling or failure in the central borehole, slots, or on the rib surface.)
   A. Pressurize flat jacks, and increase until null slot displacement is achieved.
   B. Cycle flat jack pressures.
      The pressurization-depressurization sequence is loosely based on the standard procedures testing geologic materials both in situ and in the laboratory. The first pressure level will be the estimated in situ stress, expected to be on the order of 2 MPa. Nominally five cycles will be used to reach peak pressure.
   C. Increase flat jack pressure until failure of central borehole and/or slots is observed.

4. Post-test observations
   A. De-pressurize flat jacks, and remove from slots, if possible.
   B. Inspect borehole/slots/rock surface (noting failure or displacements)
   C. Perform "post-mortems" of test site (can include post-test acoustic tomography, re-mapping of exposed surfaces, excavation of tendon of rock between the slots).

2.1.9 Test layout for heated slot tests

The second test was conducted at the 63+83 location in the South Ramp while the third test was conducted in the ECRB at the 21+25 location. In contrast to the first test (ambient temperature only), these tests include provisions for testing at elevated temperatures. Slot Test #2 was conducted at a nominal elevated temperature of 90°C. The elevated temperature test was performed for Slot Test #2 but not for Test #3 due to observed spalling along the axis of the 30.5 cm central borehole during test construction. Additionally, project-imposed schedule constraints prevented the implementation of the elevated temperature portion of this third test. For slot test # *2*, displacement measurements during pressurization were gathered at both ambient and elevated temperatures. The layout for these tests was similar to the first test, with the addition of heaters and thermocouples for the elevated temperature portion of the test.

Slot Test #2 was conducted first under ambient temperatures, and then under elevated temperatures. The initial ambient phase of the test was similar to the first test, with the constraint that maximum flat jack pressures was limited to prevent failure of the tendon or central borehole. During the subsequent heated portion of the test, the heaters were energized to induce a nominal rock temperature of 90°C.

2.1.10 Heaters and thermocouples

The number of heaters and their locations were approximately as depicted in Figure 3. This geometry and the determination of heater power and length of time required to reach nominally uniform conditions within the rock tendon were defined by scoping calculations. Type-K (Chromel/Alumel) thermocouples were used to provide temperature data and were co-located with other gages (as described elsewhere). All thermocouples were calibrated per YMP QA procedures.

2.1.11 Test procedure for heated slot test

The installation and conduct of the test involved the following steps (also taken from George and Howard, 2002):

1. Site preparation
   A. Drill dowel pin holes
   B. Mount surface deformation pins
   Once the surface deformation gages are installed, they should be monitored during subsequent hole drilling.
   C. Core 30.5 cm central hole and inspect (map locations of prominent lithophysae)
   D. Instrument central hole
   E. Drill 7.6 cm heater holes
   F. Install heaters

2. Slot cutting and flat jack installation
   Central hole and surface deformations should be monitored during slot cutting.
   A. Cut slots with HRSS
   B. Map surface of slots
   C. Install flat jacks and shims along with yo-yo gages
   D. Install instrumentation for remotely measuring pin deformations

3. Slot pressurization
   During this portion of the test, all instrumentation should be monitored. In addition, observations should be made of any spalling or failure in the central borehole, slots, or on the rib surface.
   A. Pressurize flat jacks, and increase until null slot displacement is achieved.
   B. Cycle flat jack pressures.
   The pressurization-depressurization sequence is loosely based on the ASTM standards for the plate loading test (ASTM D 4394) and for flat jack testing (ASTM D 4729). The first pressure level will be the estimated in situ stress, expected to be on the order of 2 MPa. The maximum pressure must not result in failure or gross spalling of the central borehole or slots. Nominally five cycles will be used to reach the maximum pressure. The maximum pressure will be held constant for a minimum of fifteen minutes to determine time-dependent effects.
   C. Establish constant pressure in flat jacks at estimated in situ stress.

4. Test at elevated temperature

During this portion of test, all instrumentation should be monitored. In addition, observations should be made of any spalling or failure in the central borehole, slots, or on the rib surface.

A. Increase power to heaters to reach a nominal rock temperature of 90°C.
During the heating of the rock, the flat jacks are to be bled to maintain a nearly constant pressure.
B. Cycle flat jack pressure.
The pressurization-depressurization sequence is loosely based on the standard testing procedures for both laboratory and in situ testing. The first pressure level will be the estimated in situ stress, expected to be on the order of 2 MPa. The peak pressure is expected to be on the order of 15 MPa. Nominally five cycles will be used to reach peak pressure.
C. Increase flat jack pressure until failure of central borehole and/or slots is observed.

5. Post-test observations

A. De-energize heaters.
B. De-pressurize flat jacks, and remove from slots, if possible.
C. Inspect borehole/slots/rock surface (noting failure or displacements)
D. Perform "post-mortem" of test area (can include post-test acoustic tomography, remapping of exposed surfaces, excavation of tendon of rock between the slots).

2.2 ACCURACY AND PRECISION

The accuracy of the instrumentation used for these tests directly affected the accuracy of the calculated thermo-mechanical properties. The accuracy of the calculated values was also affected by nonhomogeneities and variability in the Tptpll and Tptpul lithostratigraphic units, the precision with which instrumentation locations were measured, the precision and control of the flat jack pressures, and the accuracy with which heater power was controlled.

To ensure that the collected data met the project needs, the instruments were calibrated in accordance with applicable procedures. As stated in ASTM D 4729, due to the nature of the rock materials tested by this method it was either not feasible or too costly at this time to produce multiple specimens that had uniform physical properties. Variations observed in the data were just as likely to be due to specimen variation as to operator or laboratory testing variation. There was no accepted reference value for this test method; therefore, bias could not be determined.

2.2.1 Accuracy Requirements

The accuracy requirements for locating components of this test relative to one another are approximated as follows:

- Instrumentation locations: ± 0.01 m
- Borehole locations: ± 0.01 m
- Borehole diameter: ± .0025 m
- Heater location: ± 0.1 m
- Slot locations: ± 0.01 m
- Slot dimensions: ±0 .01 m
- Surface displacements: ± 0.001 cm

- Slot displacements: ± 0.01 cm
- Borehole displacements: ± 0.005 cm
- Flat jack pressures: ± 0.01 MPa
- Time: ± 10 seconds

2.2.2 Test Instrumentation Calibration and Instrument Error

The following test instrumentation was used for these tests:

Surface displacement - twelve (12) position transducers meeting the following specifications:

Performance
Range: 0-2" (0 – 50 mm)
Accuracy : ± 0.1% FS (linear within range; i.e., 0.1% of measured value)
Resolution: Infinite (Hybrid Potentiometer)

Electrical
Excitation: AC/DC ≤ 25 Volts
Input Impedance: 500 Ω
Output Impedance: 0-500 Ω
Environmental
Temperature: 0 to 200º F (-18 to 95º C)
Humidity:95% RH @ 75ºF
Shock: 50g for 10 ms
Vibration: 20g 20-2 kHz

Slot displacement - eight (8) sub-miniature position transducers meeting the following specifications:

Performance
Range: 0-1.50" (0-38mm)
Accuracy : ± .1% FS
Resolution: Infinite (Hybrid Potentiometer)
Electrical
Excitation: ≤ 35 Volts DC
Input Impedance: 5000 Ω ± 10%
Output Impedance: 0-5000 Ω ± 10%
Environmental
Temperature: -85 to +257º F (-65 to 161ºC)
Humidity: NEMA 3S
Shock: 100g for 6 ms
Vibration: 10-2 kHz @ 15 g

Central borehole displacement - six (6) linear displacement transducers meeting the following specifications:

Performance
Range: 0-1" (0-25mm)
Accuracy : ±0.1% FS
Resolution: Infinite (350Ω bridge)
Electrical
Excitation: 2-10 Volts AC/DC
Output: 7.0 mV/V F.S.
Environmental
Temperature: 15 to +160º F (-10 to +60ºC)

Flat jack pressure - two (2) Dynisco 861-310-10M Series strain gage pressure transducers meeting the following specifications:

Performance
Range: 0-10,000 psi (0 to 69 MPa)
Accuracy : ±.25% FS 1000 to 10000 psig
Sensitivity: .9985+00 mV psig
Electrical
Excitation: 28 Volts DC
Output: 0-10Volts DC
Environmental
Temperature: -20 to +185º F (-29 to 85º C)
Overpressure: 3 X Rated pressure

Temperature - Twelve (12) Type 'K' Thermocouples meeting the following specifications:

Performance
Range: -74F to 350F (23ºC to 176ºC) (based on adhesive)
Limits of Error : 1.1 C (0.4%)

2.2.3 Experimental/Sampling Artifacts

2.2.3.1 Control/Determination of Independent Conditional Variables

The independent variables in this experiment were flat jack pressure, flat jack location, heater power, heater geometry, displacement measurement locations, thermocouple location, and time. Measurement errors were typically random and resulted from instrument calibration errors and the accuracies with which locations, times, displacements, pressures and temperatures can be measured. Variability in independent variables includes the accuracy to which heater power was controlled.

2.2.3.2 Control/Determination of the Boundary Conditions

The boundaries of the rock mass affected by the slot pressurization are some distance away from the pressurized tendon. Displacement measurements outside the slots were made to confirm the extent of the induced displacements. The boundaries of the heated volume were at ambient conditions. Thermocouples were placed in the drift and on the drift walls such that any changes in ambient temperature could be monitored.

3. PRE-TEST CALCULATION / ANALYSIS / MODEL PREDICTIONS

3.1 PRE-TEST CALCULATION / ANALYSIS / MODEL PREDICTIONS

Pre-test simulations of the Pressurized Slot Tests were completed and documented per AP-3.12Q prior to test initiation. Pre-test simulations were based on the design geometry discussed above - including slot dimensions, flat jack locations, assumed ranges of lithophysae content and distribution, and the intact rock elastic properties. Additional calculations were run with different values of elastic modulus and no lithophysae. The predictions from these calculations were compared to the test data to estimate the rock mass modulus, a combined effect of the elastic properties of the intact rock and the variation due to the presence of lithophysae and fractures.

As a precursor to the pre-test calculations, scoping analyses were performed to confirm some of the decisions made for the design of the slot tests, particularly those regarding overall test geometry. These scoping predictions of the measured displacements were submitted to the YMP Technical Data Management System (TDMS) (SNL, 2001a). A complete description of these scoping analyses can be found in the YMP records package accompanying this TDMS submittal. The scoping analyses provided information on the rock mass response over a reasonable range of geometries, material properties, and loading conditions. Test design allowed for possible displacements that would fall within the range of the measuring devices, and were still potentially large enough to be correlated to predictions based on varying rock mass modulus. The following values were predicted from the scoping analyses for several test geometry configurations and assumptions:

- Rock displacements in the central borehole
- Rock displacements across the tendon at the drift wall
- Rock displacements across the slots at the drift wall
- Rock displacements within the slots at the center of and around the edge of the flat jacks (include both sides of slots)
- Potential for failure in these locations

A series of scoping calculations were conducted for the configuration shown in Figure 3 using a simple elastic model implemented in the finite element code JAS3D. The range of dimensions modeled in the calculations is shown in Table 5. Some of these dimensions were assumed values based on previous experience. The design borehole diameter was chosen based on the available drilling rig for its construction (30.5 cm). Also, rock properties for the Topopah Spring (TSw) lower lithophysal unit were used for these calculations. The properties were measured in the laboratory from samples taken from an outcropping of the TSw lower lithophysal unit near Busted Butte (Price et al., 1985). These values are:

Young's modulus: 15.5 GPa
Poisson's ratio: 0.16
Unconfined compressive strength: 16.2 MPa
Axial strain at failure: 0.00123

Table 5. Slot test dimensions used in scoping analyses

Dimension	Range Modeled	Comment
Flat jack dimensions	0.81m x 0.81m	Standard flat jack dimensions
Borehole Diameter (D)	10.2-30.5 cm	Design dimension 1 foot (30.5 cm) set by drilling size available
Tendon Thickness (T)	1-2 m	Design dimension 4 feet (1.2m) for D/T ratio = 0.25
Slot Height (H_s)	1.5 m	Typical height
Slot Depth (S_d)	1.5 m	Typical depth
Flat jack Inset Distance (from drift wall to front edge of flat jack)	35 cm (centered in slot), 10 cm (near drift wall)	Design dimension 10 cm to allow large displacements at drift wall
Flat jack operating pressures	0 MPa to 30 MPa	Standard range

Simulations were first used to evaluate the effect of the ratio between the borehole diameter and tendon thickness (D/T) on the magnitude of displacements within the borehole. These initial calculations also placed the flat jacks in the center of the slots. These simulations revealed that borehole displacement increased with borehole diameter. The largest borehole was predicted to have a horizontal closure of about 1.2 mm, assuming a rock mass modulus equal to the intact rock measured value. Results from additional simulations varying the D/T ratio are included below.

Simulations were performed with the flat jacks moved closer to the drift wall (10 cm from wall to edge), to allow for maximum possible displacements at the drift wall. Figure 7 compares tendon thickness displacements for the different configurations. Note that when the flat jacks were located in the center of the slots, the direction of the displacements at the drift wall was not in a consistent direction. This would make it difficult to use these measurements to infer a value for rock mass modulus. Moving the flat jacks closer to the drift wall would cause a more consistent displacement pattern to occur, making the evaluation of the data more reliable. Thus, the decision was made to place the flat jacks as close to the drift wall as possible, given the constraint that the compressed rock zone must be beyond the expected damage zone near the drift wall. These results also confirm the previous conclusion regarding increasing borehole displacements with increasing D/T ratio.

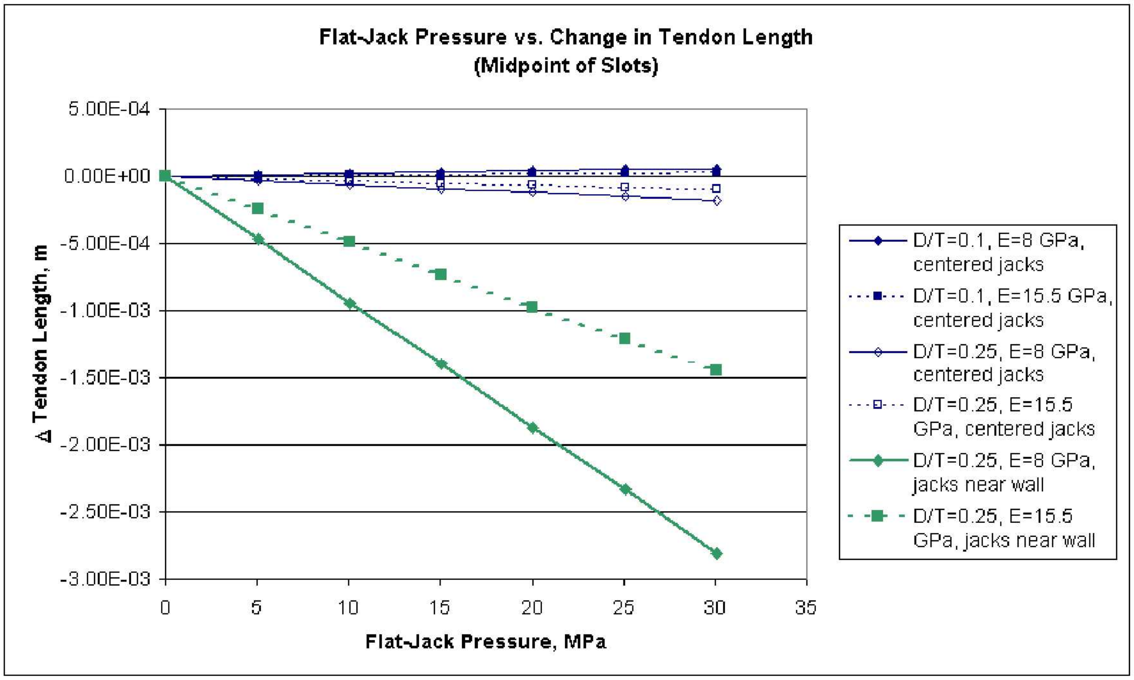


Figure 7. Predicted midpoint displacements, based on D/T ratio and flat jack placement (DTN SN0112T0812501.001)

Ultimately, the pre-test calculations that were performed for each individual test geometry were run at several values of rock-mass modulus. Furthermore, the TSw2 lower lithophysal zone (Tptpll) has many sections where lithophysae take up to 30% of the volume of the rock. Therefore, each test site required an estimation of the percent volume contained in lithophysae, and a distribution of volume sizes. For these scoping analyses, a preliminary attempt to randomly distribute lithophysae in the mesh has been completed; the lithophysae take up 12% of the volume of the rock immediately surrounding the test. Four sets of simulations have been completed, using elastic modulus values of either 8 or 15.5 MPa, and including either 0% or 12% lithophysal space in the rock. For a slot test location where the measured intact rock elastic modulus is 15.5 MPa, and the estimated lithophysal void space is 12%, that set of calculations would be the predictions for the test. Figures 8, 9, and 10 show displacement predictions for the midpoint of the slots, the top and bottom of the slots, and vertically and horizontally in the borehole, respectively, for these four scenarios. Note the significant variation in expected magnitudes for the different cases. Reducing the expected rock mass modulus approximately in half results in nearly doubling the magnitude of displacement, as would be expected. Also, introducing the presence of 12% lithophysal cavities also approximately doubles the predicted displacements. The maximum magnitudes of these displacements range from 1-4 mm, which is a variability much larger than would be encountered by normal operational standard deviation of the instruments. Therefore, these measurements can be used to reach confident conclusions regarding rock mass modulus values. Also note in Figure 9, that for the lithophysal cases, the top and bottom of the tendon do not necessarily undergo the same amount of displacement. This is due to the random nature of the placement of the lithophysae. Another random placement would likely produce different results. Part of the as-built test geometry that was considered for the test analyses was mapping the locations of visible lithophysae around the test configuration, and transferring those locations to the computational mesh.

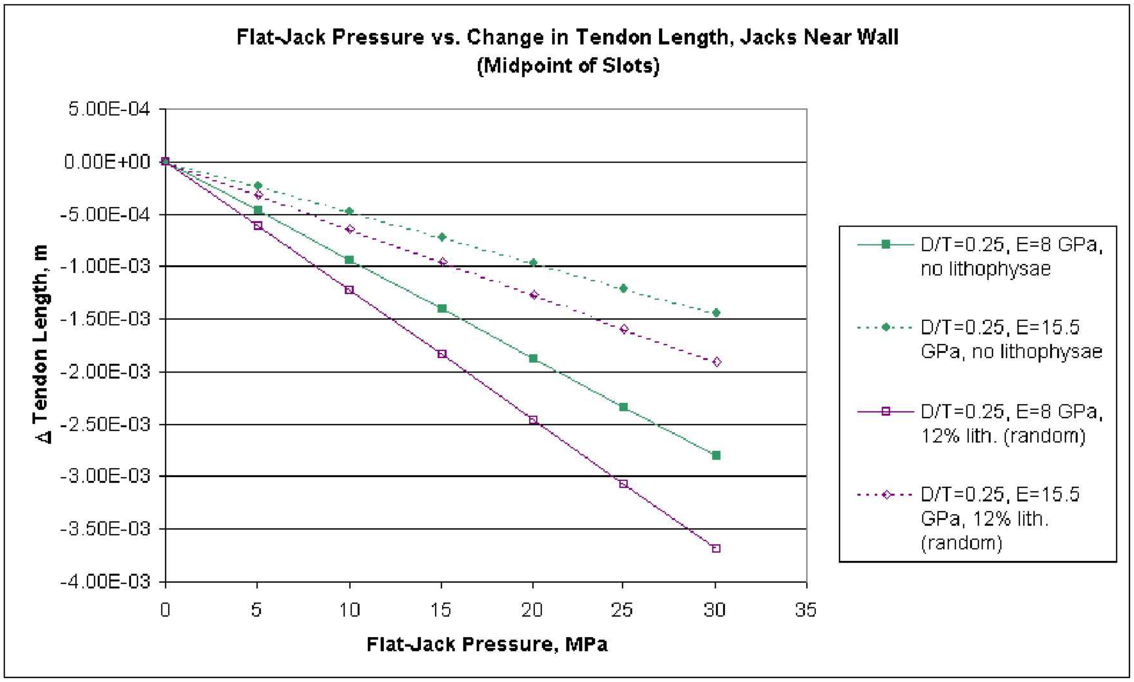


Figure 8. Displacement predictions, midpoint of slots, for different values of modulus and lithophysal content. placement (DTN SN0112T0812501.001)

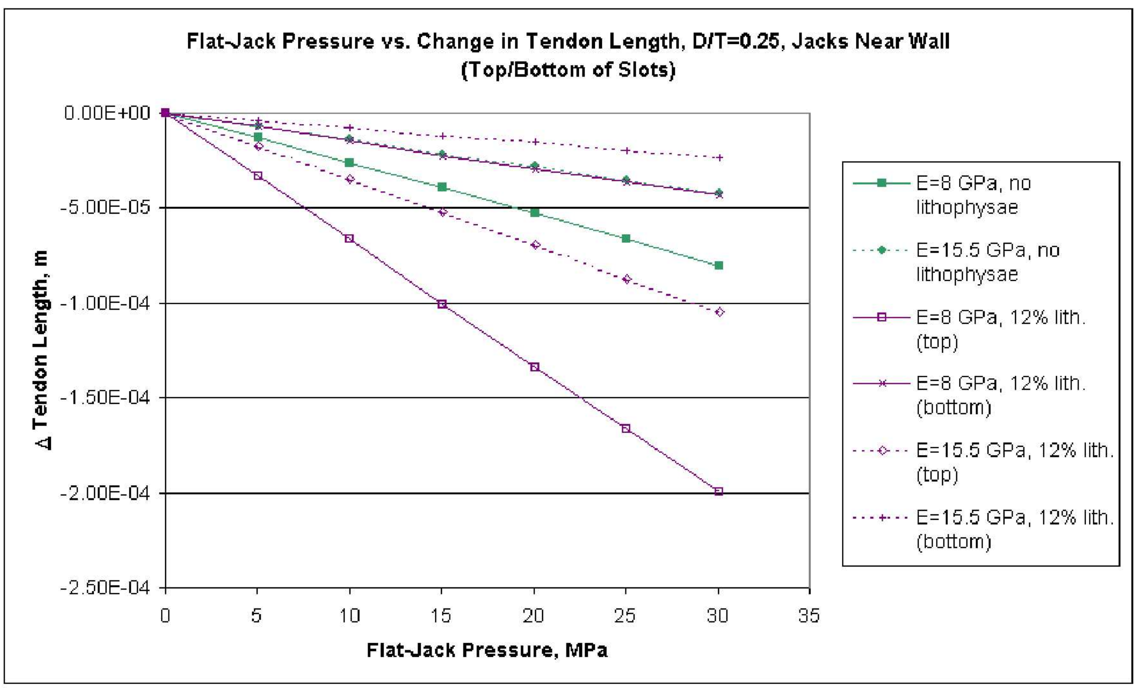


Figure 9. Displacement predictions, ends of slots, for different values of modulus and lithophysal content. placement (DTN SN0112T0812501.001)

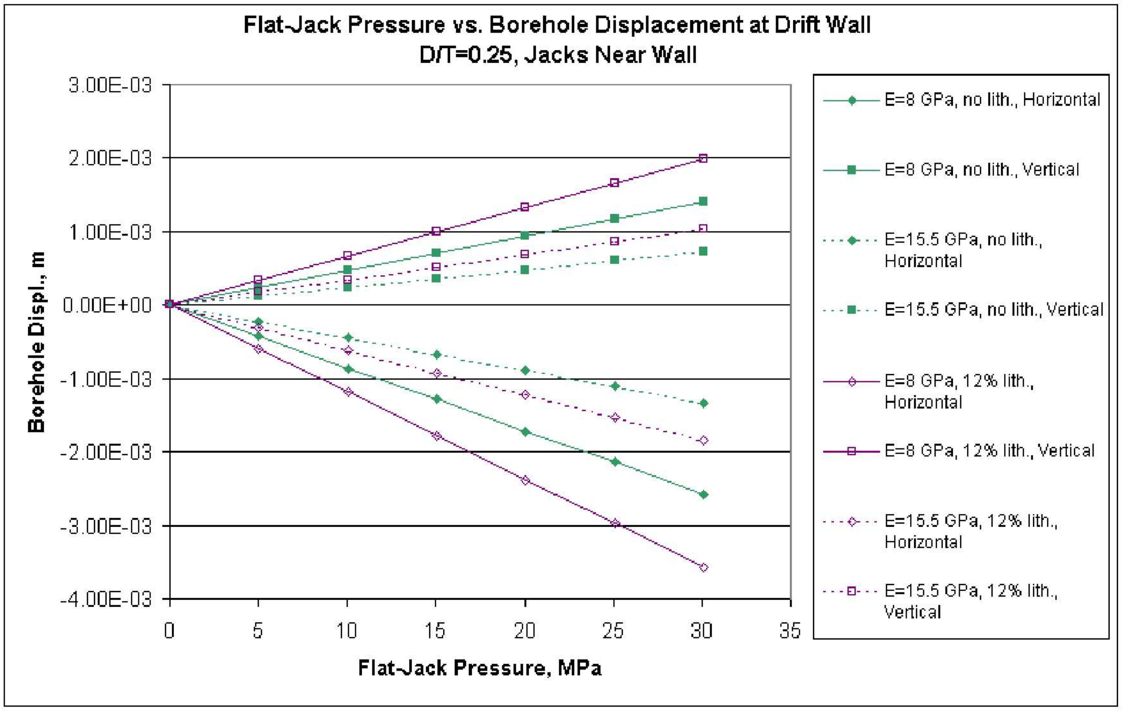


Figure 10. Displacement predictions, in the central borehole, for different values of modulus and lithophysal content. placement (DTN SN0112T0812501.001)

The scoping analyses presented here indicate the methodology that was used for the pre-test predictions and post-test analysis of each individual slot test:

1. The as-built geometry, including slot dimensions and flat jack locations, were included in the computational mesh.
2. A set of calculations using the intact rock elastic properties and the as-built geometry provided the pre-test predictions for the measurement locations.
3. Several other calculations were run with different values of elastic modulus and no lithophysae. The predictions from these calculations were compared to the test data to estimate the rock mass modulus, a combined effect of the elastic properties of the intact rock and the variation due to the presence of lithophysae and fractures.

3.2 IDENTIFICATION OF COMPUTER SOFTWARE

The finite element code JAS3D (Blanford, 1999) was used for pre-test thermal-mechanical test predictions, and to analyze the ambient data from these tests. The JAS3D finite element program has been developed by SNL to provide a versatile iterative approach to quasi-static three-dimensional finite element calculations. The continuum mechanics modeled by JAS3D are based on two fundamental governing equations. The kinematics are based on the conservation of momentum equation, which can be solved either for quasi-static or dynamic conditions (a quasi-static procedure was used for these analyses). The stress-strain relationships are posed in terms of the conventional Cauchy stress. JAS3D has not yet been qualified per YMP QA procedures (this qualification is currently is progress); however, it has a large community of users inside and outside SNL for problems ranging from plane crash simulations to viscoelastic simulations of rubber/concrete interaction. JAS3D includes at least 30 different material models.

3.3 ANALYSIS AND MODELING DURING AND AFTER TEST

Post-test analyses of each test were conducted by performing simulations in a manner similar to the scoping simulations discussed above. These numerical modeling simulations included the as-built geometry - including slot dimensions, flat jack locations, and lithophysae locations and volumes - and the intact rock elastic properties. Additional calculations were run with different values of elastic modulus and no lithophysae. The results from these calculations were compared to the test data to determine the rock mass modulus and failure strength, resulting from the combined effect of the elastic properties of the intact rock and the variation due to the presence of lithophysae and fractures.

4. SLOT TEST #1

This section describes the displacement data obtained from Pressurized Slot Test #1, as well as the procedure used for calculating rock mass mechanical properties (rock mass modulus and Poisson's ratio) from the measurements. This slot test was conducted in the Exploratory Studies Facility (ESF) at station 57+77, in the Topopah Springs lower lithophysal unit Tptpll. (The Scientific Notebook, which was opened before the test site was constructed, lists the site as 57+70. The surveyed location of the test was actually 57+77.) The test data have been submitted to the TDMS (SNL, 2002a). The rock mass mechanical properties data were developed by comparison of numerical model predictions for displacements with the measured displacements from the actual test. These developed data have also been submitted by SNL to the YMP TDMS (SNL, 2002b). The developed data that were submitted to the TDMS are presented in Table 6.

Table 6. Data Submittals for the Pressurized Slot Test #1, 5/8/2002 (SNL, 2002b)

Data Descriptor	**Data Value**
Slot Test Location	Exploratory Studies Facility Station 57+77, borehole azimuth 273° 32' 34.3", in the Tptpll unit
Rock Mass Elastic Modulus, GPa	0.50 GPa ±0.30 GPa
Poisson's Ratio	0.20

This section documents the analysis performed to develop the rock mass mechanical properties. For such documentation, the following subjects will be discussed:

- A brief discussion of the test setup.
- A brief discussion of the test results.
- A discussion of the analytical procedure and input parameters.
- Presentation of results and rationale for selection of the rock mass mechanical property values.

4.1 TEST SETUP

This test is the first of three pressurized slot tests that have provided thermal-mechanical properties of the Tptpll lithostratigraphic unit. The test layout is shown in Figure 3. At the selected test location, the rib surface was instrumented to monitor deformations, and two vertical slots were cut in the rib to create a “tendon” of rock between them. Flat jacks and bearing plates were placed in the slots, and they were instrumented to measure displacement across the slot. Subsequent loading-unloading cycles provided a pressure/deformation history that was evaluated to determine the rock mass deformation modulus. The borehole in the center of the tendon between the slots was used to gather more information by measuring the deformation across the borehole diameter as the slots were loaded. As the pressures in the flat jacks increased, the stress around the borehole also increased, possibly resulting in failure of the rock. The failure stress of the rock can be determined from the borehole observations. Finally, the rock mass strength can be evaluated by increasing the flat jack pressure until gross failure of the tendon of rock between the flat jacks occurs. Because this test was conducted in a complex configuration, numerical modeling of the test was required during both test design and for post-test analyses of the results.

The as-built locations of the slots, platens, and borehole for slot test #1 are shown in Figure 11. A tendon of rock 123cm wide was created by cutting two vertical slots in the rib. A 30.5cm diameter, 150cm deep borehole was centrally located between the slots, and was used to measure rock deformation. The slots were designed to be nominally 3.8cm wide, 122cm deep and extend to a height of 214cm above the pre-cast invert. The as-built dimensions of the two slots are drawn to scale in Figures 12 and 13. The left slot was cut to a depth of 185 cm with respect to the axis of the borehole, and the right slot to a depth of 178 cm. Flat jacks with integral bearing plates for loading the rock tendon were placed in the slots. These flat jack platens were built to 91.4 cm (36 in.) on a side. The as-built dimensions are included in the scientific notebook for this test, Rock Modulus Test #1 Located at 57+70 of ESF, SN-SNL-SCI-027-V1.

The initial test site, selected by representatives of SNL and the Los Alamos National Laboratory (LANL) Test Coordination Office (TCO), is located on the right rib at station 57+77 in the South Ramp. The 30.5cm diameter central hole and finished slots was evaluated for lithophysae content.

Platen Dimensions & Installation Locations for Left Slot 1/A & Right Slot 2/B

(All dimensions in meters unless noted otherwise)

1. Platen assembly size = .914 x .914 (nominal width of 3.80 cm)
2. Flatjack size centered inside platens = .813 x .813
3. Slot width varied from 3.90 cm to 4.445 cm
4. All installed gage and flatjack assembly coordinates referenced to center line of borehole

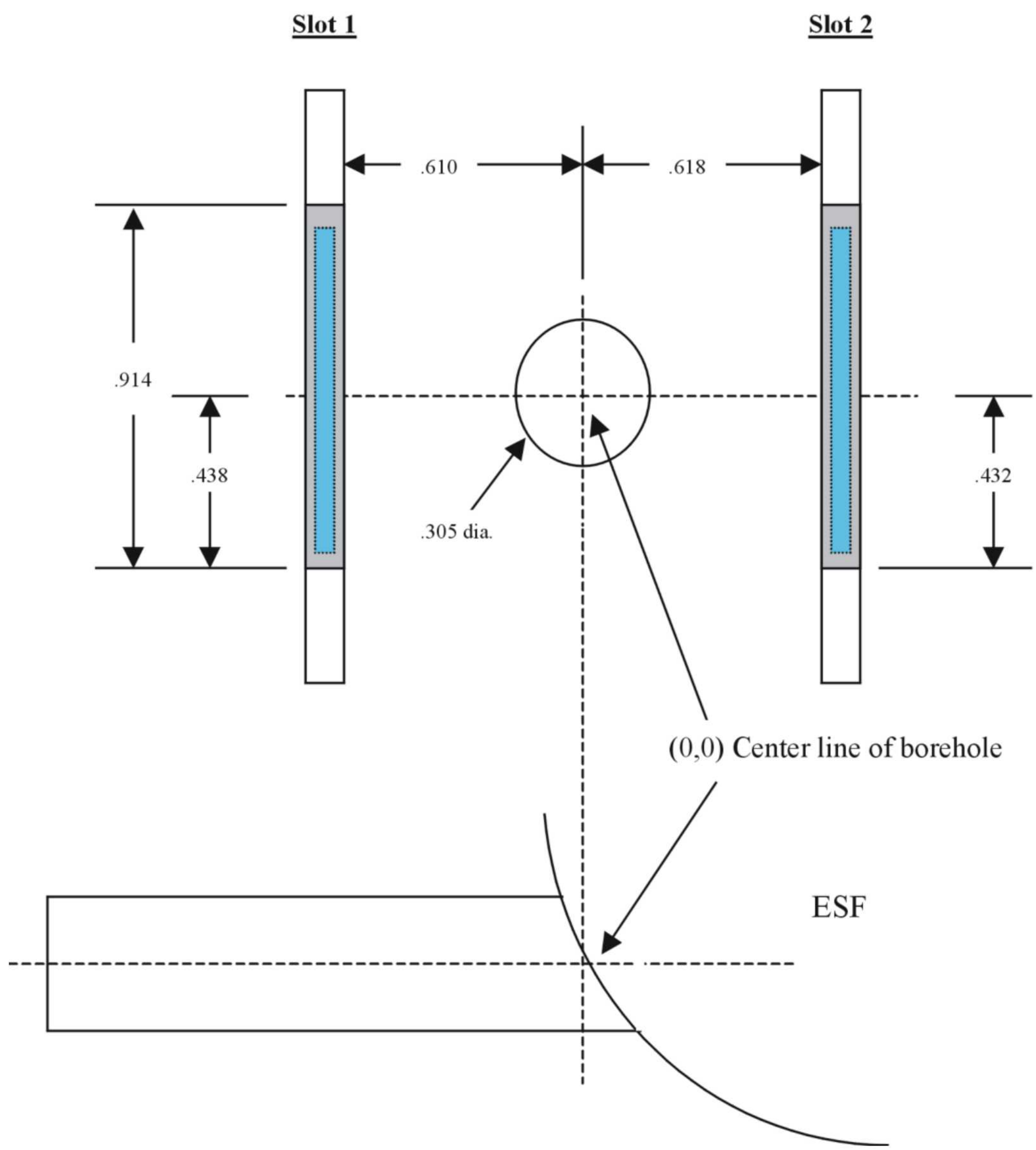


Figure 11. Platen dimensions & installation locations for Left Slot 1/A & Right Slot 2/B, Slot Test #1

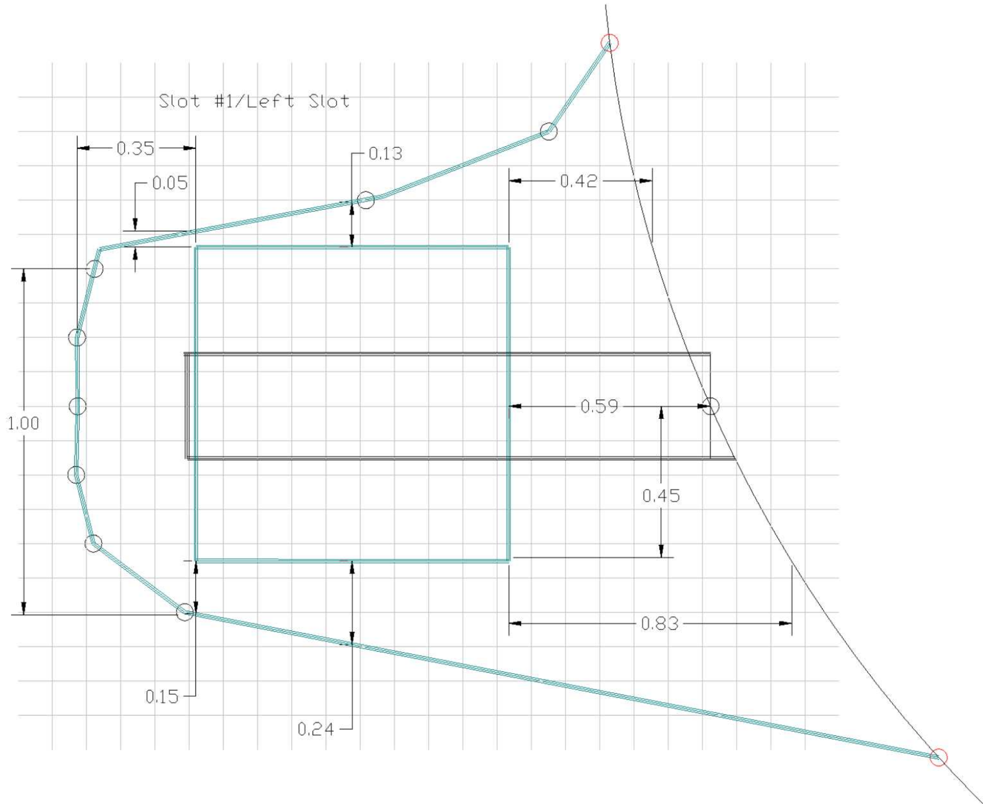


Figure 12. As-Built Dimensions of the Left Slot, Slot Test #1 (drawn on 0.1m grid)

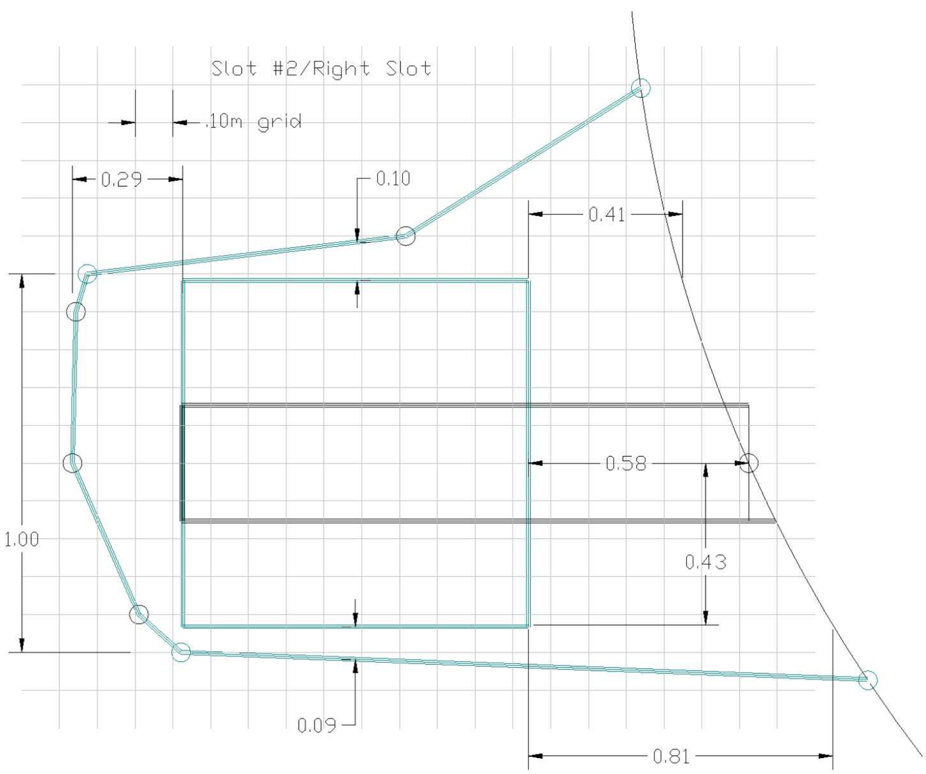


Figure 13. As-Built Dimensions of the Right Slot, Slot Test #1 (drawn on 0.1m grid)

Of the many displacement measurements collected for this test, the displacements within the central borehole are of primary interest. Six linear displacement transducer gages employing cantilevered strain gages were installed within the central borehole. The closure gages are numbered 1-6, and their location in the borehole with their xyz coordinates, are illustrated in Figure 14.

Center Borehole Closure Gage Installation Locations

(All locations in meters unless noted otherwise)

1. (X,Y,Z) Coordinates where X = Horizontal, Y = Depth, Z = Vertical
2. All coordinates preliminary pending final survey results
3. Depth of Center Borehole approximately 1.504 meters
4. ST1-BHD-1, ST1-BHD-3 & ST1-BHD-5 installed to measure vertical closure.
5. ST1-BHD-2, ST1-BHD-4 & ST1-BHD-6 installed to measure horizontal closure.

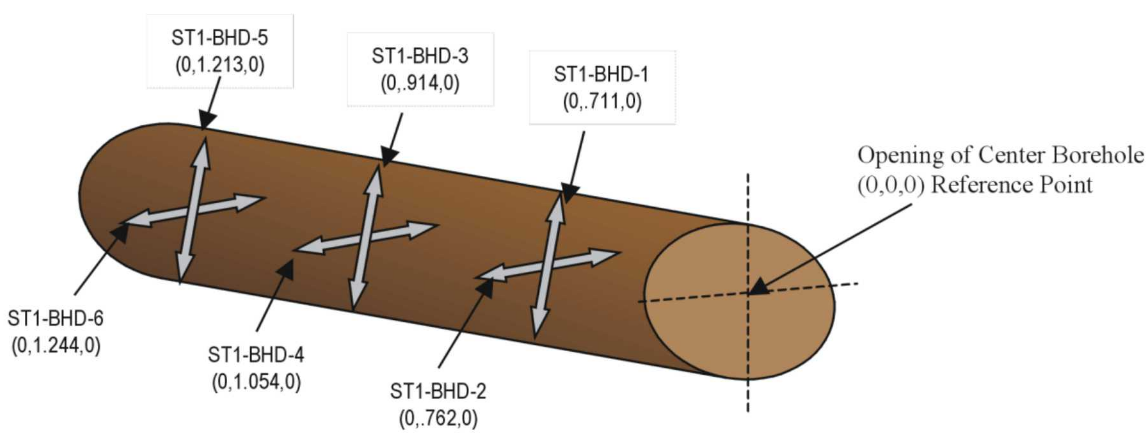


Figure 14. Center Borehole Closure Gage Installation Locations, Slot Test #1

4.2 TEST RESULTS

The rock quality at the test location was poor. Prior to test initiation, the rock in the test region was highly fractured, and there were at least three sections of the borehole that had undergone significant rockfall. In addition, the rock was very porous and had numerous lithophysae in the test region.

The pressurized slot test #1 was performed on May 8, 2002. The pressure in the flat jacks was raised to a maximum of 880 psi (6.07 MPa) during the ~2.5-hour-long test. A time history of the average flat jack pressure, along with a fitted curve used as input to the calculations, is shown in Figure 15. The test's Principal Investigator noted that starting at a pressure of about 310 psi (2.14 MPa), significant scaling of the rock in the borehole and on the drift wall surrounding the borehole began. This scaling continued periodically up to the maximum pressure, with some significant fracturing events occurring during that interval. Therefore, the analysis team decided that only the displacement-pressure data up to the 2.1-MPa point should be used to determine a rock mass modulus value; beyond that point, the rock behaved in an inelastic manner characterized by some combination of fracturing, scaling, and lithophysae compression.

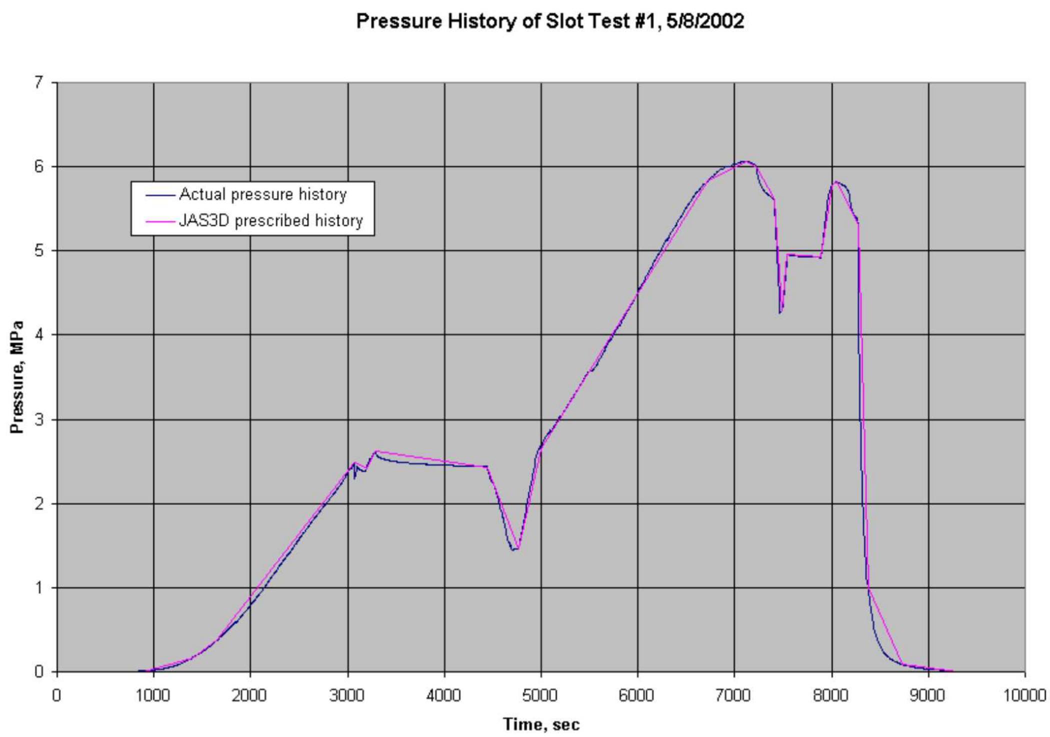


Figure 15. Flat jack pressure history for Slot Test #1 (DTN SN0207F4102102.001)

The closure measurements from inside the borehole are given in Figure 16. Positive displacement in this case means closure, and negative means expansion. The horizontal gages (gages 2, 4, and 6) are closing during the test, and the vertical gages (1, 3, and 5) are expanding. Note that the front gages (1 and 2) exhibit higher displacements than the middle gages (3 and 4), and more so than the back gages (5 and 6).

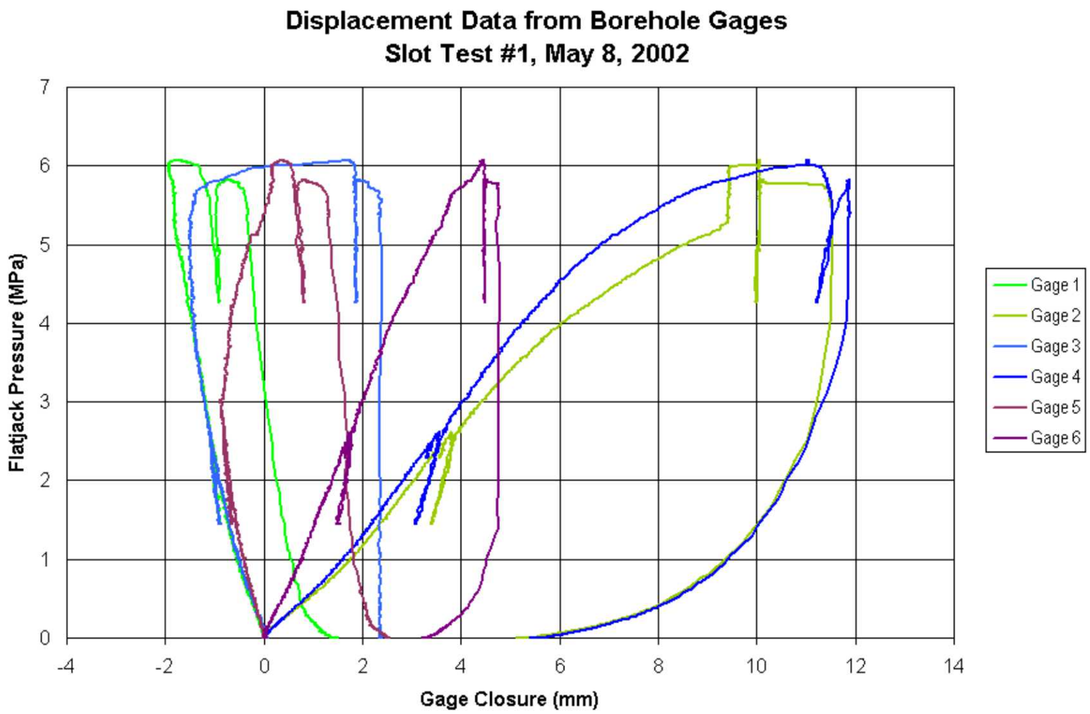


Figure 16. Closure Data from the Central Borehole, Slot Test #1 (DTN SN0207F4102102.001)

4.3 ANALYTICAL PROCEDURE

A mechanical stress analysis utilizing appropriate initial stress and boundary conditions, as-built test geometry, and an appropriate material model, is required in order to derive rock mass mechanical properties from the test data. Two types of analyses were performed to derive the rock mass modulus and Poisson's ratio for this test. First, a closed-form solution for horizontal stress applied near an underground borehole called a Kirsch solution was used to estimate elastic constants. From this solution, initial estimates of elastic modulus=0.48 GPa and Poisson's ratio of 0.20 were estimated. The value of 0.20 was very similar to the Poisson's ratio value of 0.16 obtained for Tptpll intact samples retrieved from an outcrop at Busted Butte (Price et al., 1985). The modulus value differed significantly from the intact rock value obtained by Price et al., of 15.5 GPa; this difference indicates the decrease in quality of the in situ rock due to the ubiquitous presence of fractures and lithophysae.

The estimates from the Kirsch solution were used as input to the second analytical method, which was ultimately used to derive the values presented here. This analysis required the use of JAS3D, a three-dimensional finite element program developed by SNL, and designed to solve large quasi-static nonlinear mechanics problems. Several constitutive material models are incorporated into the program, including models that account for elasticity, viscoelasticity, several types of hardening plasticity, strain rate dependent behavior, damage, internal state variables, deviatoric and volumetric creep, and incompressibility. JAS3D, Version 1.6.F, is qualified per YMP Procedure AP-SI.1Q, Rev. 3/ICN 4, Software Management.

A summary of the parameters required for the performance of the JAS3D calculations is shown in Table 7. A mesh was generated using the as-built dimensions of the South Ramp drift, slots, borehole, and flat jack and closure gage locations. The selected material model was the elastic model, to determine the deformational character of the in situ rock as a rock mass. For this analysis, no lithophysae were inserted into the mesh; this is consistent with an elastic rock mass problem definition. Initial stress conditions were taken from measurements made elsewhere in the ESF. The problem definition called for the excavation of the slots and borehole to allow for stress relief, then the application of the flat jack pressurization.

Table 7. Input Parameters for Analysis of Pressurized Slot Test #1

Parameter		**Info (Source DTN, Version number, etc.)**
Analysis code	JAS3D	Version 1.6.F, Software Tracking Number 10023-1.6-00; qualified per procedure AP-SI.1Q, Rev. 3/ICN 4, Software Management; completed qualification on 7/17/2002, re-installed on local network 8/2/2002.
Material model	Elastic	No lithophysae in mesh
Slot/flat jack location, geometry coordinate values	See Figures 11, 12, 13, 14	Scientific Notebook for Rock Modulus Test #1 Located at 57+70 of ESF, SN-SNL-SCI-027-V1;
Initial stresses	Vertical: σ_v = 4.3 MPa Horizontal: σ_H = 3.0 MPa (parallel to Drift) σ_h = 2.0 MPa (parallel to borehole)	SNL (2000); values from Alcove 6, located at ESF Station 37+37
Dry Bulk Density of Host Rock	1910 kg/m^3	Price et al. (1985), based on lab tests on samples collected from Tptpll unit from Busted Butte outcrop
Poisson's ratio	0.16, 0.20	Price et al. (1985), for value of 0.16 from lab samples; Kirsch analysis of applies horizontal stress near a borehole for value of 0.20
Flat jack loading conditions	Increase the flat jack load up to 6.068 MPa (880 psi) over 2.5 hours	Slot Test #1 test data (SNL, 2002a); see Figure 15
Test data for comparison	See Figure 16	Slot Test #1 test data (SNL, 2002a)

4.4 COMPARISON OF DATA TO ANALYSES

Figures 17-19 present comparisons between the measured data from the front, middle, and back borehole gages, respectively, and the predicted results from four JAS3D runs, where the modulus and Poisson's ratios are different. Six sets of mechanical properties are represented in the figures:

- Rock mass modulus=0.50 GPa, Poisson's ratio=0.20
- Rock mass modulus=0.50 GPa, Poisson's ratio=0.16

- Rock mass modulus=0.55 GPa, Poisson's ratio=0.20
- Rock mass modulus=0.65 GPa, Poisson's ratio=0.20
- Rock mass modulus=0.70 GPa, Poisson's ratio=0.20
- Rock mass modulus=0.80 GPa, Poisson's ratio=0.20

Note that the predictions for the vertical gages for all three locations are pretty close to the measured data up through the load of about 2.1-2.5 MPa, when the first signs of rock fall within the borehole occurred. There is a more significant variation in results, for both the different sets of properties and the match of predicted and measured at the three gage locations, for the horizontal gages. The data from front gages have nearly the same slope as the predictions for E=0.50 GPa after the flat jack pressure reaches 0.7 MPa. The middle gages were located near the center of the platens, and thus were chosen to determine the rock mass properties. Figure 20 shows the measured and predicted displacements for the middle gages, zooming in on the pressure range (0-2.5 MPa) before the rock began failing. A visual inspection of the plot indicates that a modulus in the range of 0.50-0.55 GPa fits the data the best. The modulus value of 0.50 GPa fits the horizontal and vertical data better up to a flat jack pressure of about 1.5 MPa; the predictions using E=0.55 GPa are somewhat better in the range up to 2.5 MPa. The value of 0.50 GPa seems more representative here because its predictions fit the data better during the early period of the test, when the effects of inelastic behavior and fracturing are not yet important. There is very little difference between the predictions using Poisson's ratio values of 0.16 and 0.20; the value of 0.20 is chosen because it is a better match in the early stages of the test. The data from the rear gages are significantly steeper than the predictions and may indicate a less damaged zone further from the drift wall. The predictions using 0.80 GPa still do not match the low displacements at this location. It is possible that a value of 1 GPa may be more representative of this rock away from the fractured damage zone. However, as these values are to be used for engineering design in the drift, the more conservative value of 0.50 GPa is selected as the rock mass modulus for this test. A deviation of ±0.30 GPa will be noted to indicate the variations observed from visual inspection of the rock, from the test data, and from the numerical analyses.

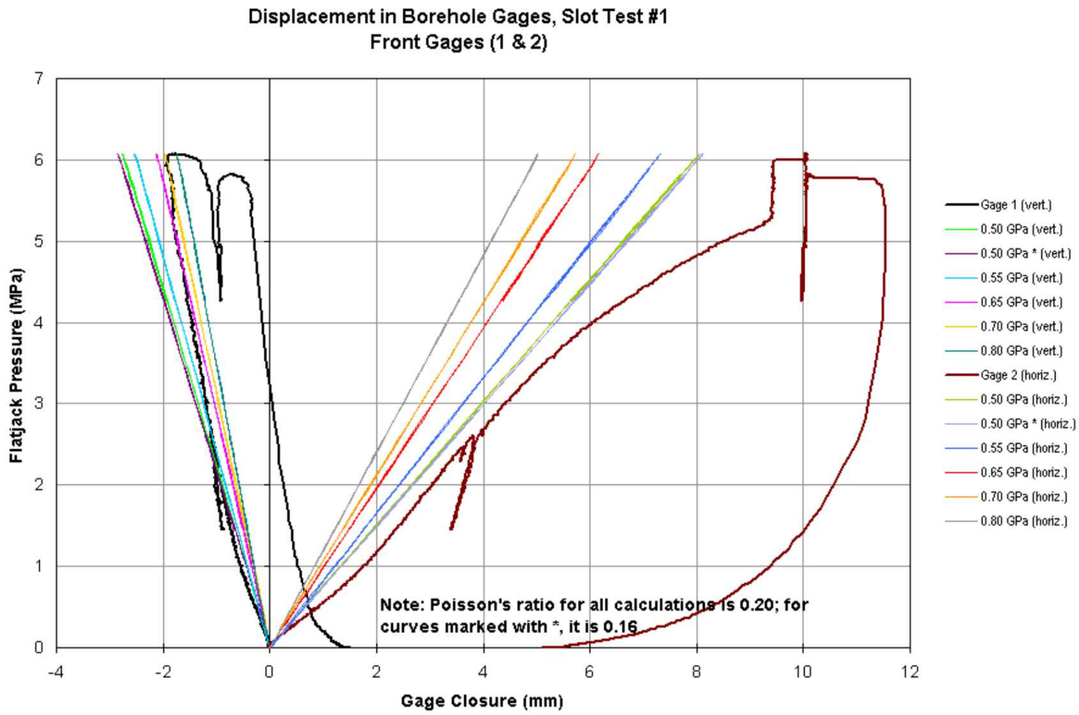


Figure 17. Displacements in Borehole Gages #1 and 2, Measured vs. Predicted (Slot Test #1) (DTN SN0207F4102102.001)

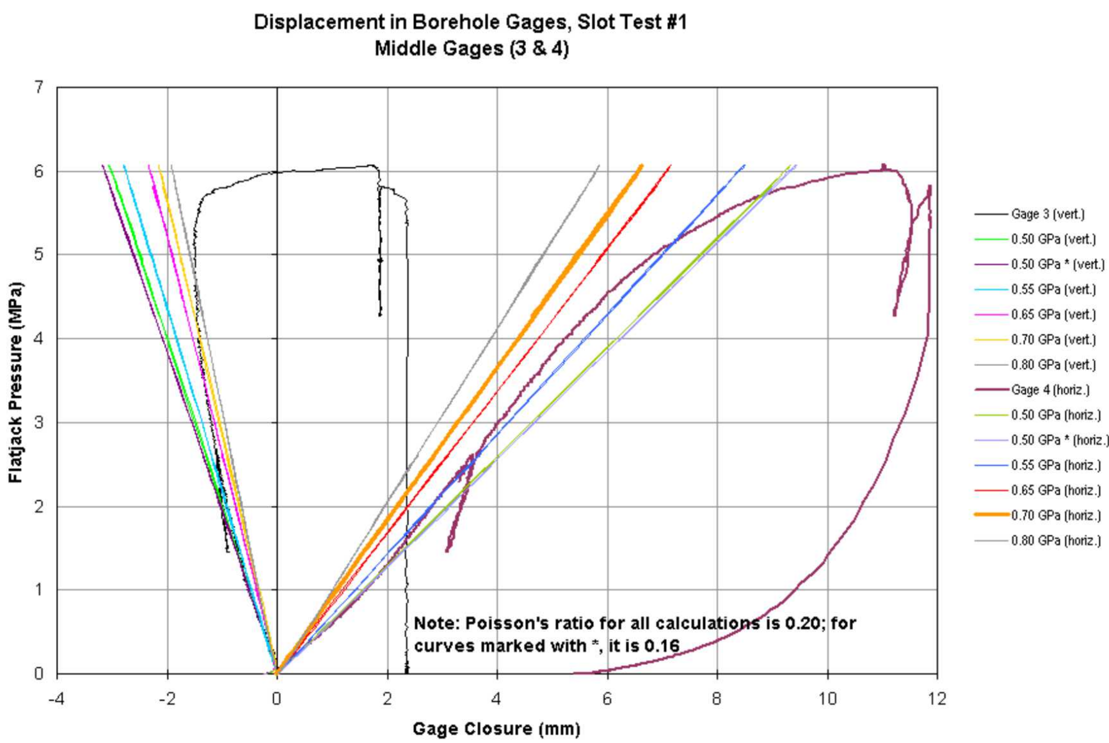


Figure 18. Displacements in Borehole Gages #3 and 4, Measured vs. Predicted (Slot Test #1) (DTN SN0207F4102102.001)

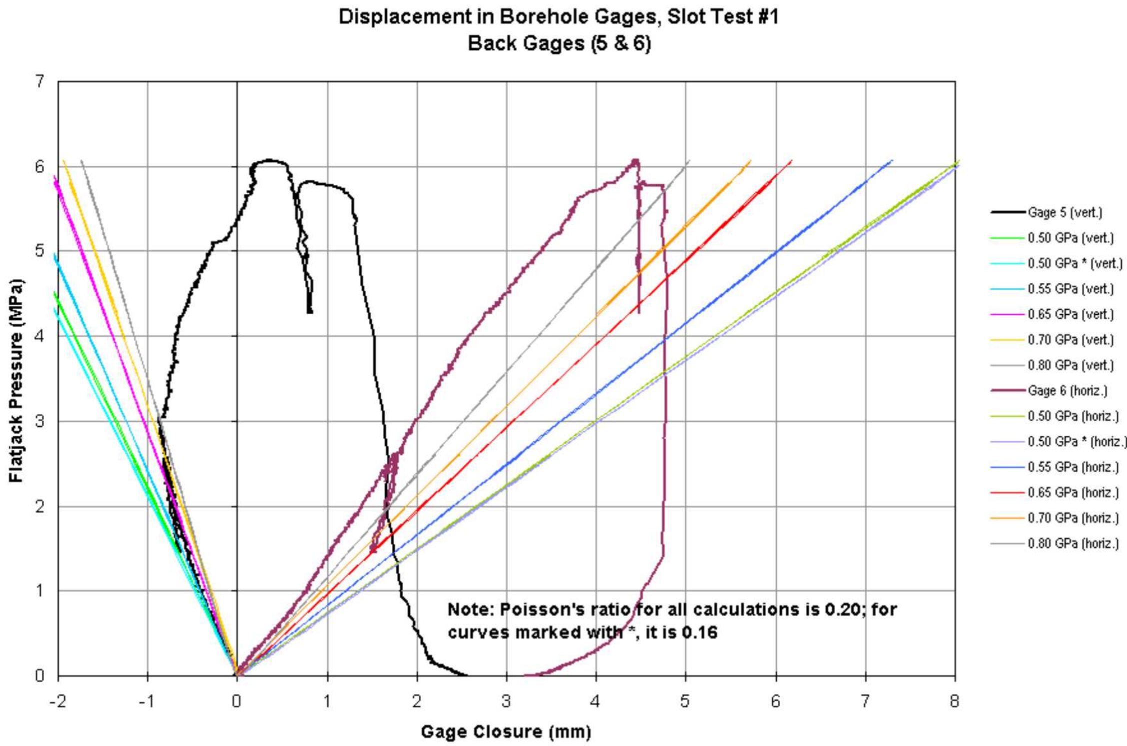


Figure 19. Displacements in Borehole Gages #5 and 6, Measured vs. Predicted (Slot Test #1) (DTN SN0207F4102102.001)

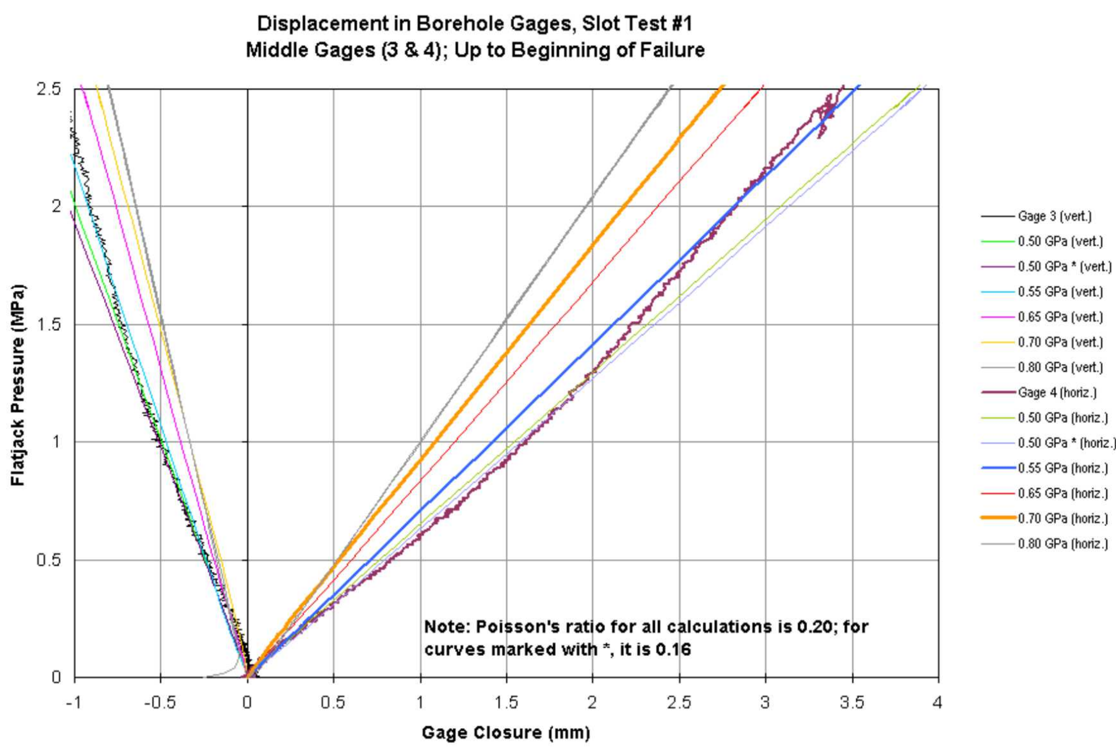


Figure 20. Displacements in Borehole Gages #3 and 4, in Elastic Region (Slot Test #1) (DTN SN0207F4102102.001)

4.5 CONCLUSIONS

The first pressurized slot test in the Topopah Springs lower lithophysal unit produced data that can be used, along with numerical analyses, to obtain rock mass values for mechanical properties such as deformation modulus and Poisson's ratio. Using JAS3D, a mechanical code qualified under YMP QA procedures, the following properties were derived: rock mass modulus = 0.50 GPa ±0.30 GPa, and Poisson's ratio = 0.20. These values are specific to the location of the test. The rock mass quality at the test site was poor due to the presence of fractures and large lithophysae.

5. SLOT TEST #2

This section describes the displacement data obtained from Pressurized Slot Test #2, as well as the procedure used for calculating rock mass mechanical properties (rock mass modulus and Poisson's ratio) from the measurements. This slot test was conducted in the Exploratory Studies Facility (ESF) at station 63+83, in the Topopah Springs upper lithophysal unit Tptpul. The data here were developed by comparison of numerical model predictions for displacements with the measured displacements from the actual test. The measured displacements, temperatures and pressures from Slot Test #2 were obtained under Supplement V controls from the scientific notebook for the pressurized slot tests, Pressurized Slot Testing for Determination of Rock Mass Modulus, Strength, and Thermal Expansivity of Tptpll Lithostratigraphic Unit, SN-SNL-SCI-027-V1. The test data have been submitted to the TDMS (SNL, 2002c), as well as the developed rock mass mechanical properties data (SNL, 2002d). The developed data that have been submitted to the TDMS are presented in Table 8. The deviation values indicated for the elastic moduli are to be taken as approximations only, based on the ranges of values used in the numerical analyses.

Table 8. Data Submittals for the Pressurized Slot Test #2, 10/15/2002-10/30/2002 (SNL, 2002d)

Data Descriptor	**Data Value**
Slot Test Location	Exploratory Studies Facility Station 63+83, borehole azimuth 276° 46' 31.2" in the Tptpul unit
Rock Mass Elastic Modulus, ambient conditions (temperature ≈ 25°C), GPa	3.0 GPa ±0.5 GPa
Rock Mass Elastic Modulus, heated conditions (temperature ≈ 90°C), GPa	1.5 GPa ±0.5 GPa
Poisson's Ratio	0.20

This report documents the analysis performed to develop the rock mass mechanical properties. For such documentation, the following subjects will be discussed:

- A brief discussion of the test setup.
- A brief discussion of the test results.
- A discussion of the analytical procedure and input parameters.
- Presentation of results and rationale for selection of the rock mass mechanical property values.

5.1 TEST SETUP

This test is the second of three pressurized slot tests that have provided thermal-mechanical properties of the Tptpul (upper lithophysal) and Tptpll (lower lithophysal) lithostratigraphic units. The nominal test layout is shown in Figure 3. At the selected test location, the rib surface was instrumented to monitor deformations, and two vertical slots were cut in the rib to create a "tendon" of rock between them. Flat jacks and bearing plates were placed in the slots, and they were instrumented to measure displacement across the slot. Subsequent loading-unloading cycles provided a pressure/deformation history that was evaluated to determine the rock mass deformation modulus. The borehole in the center of the tendon between the slots was used to gather more information by measuring the deformation across the borehole diameter as the slots were loaded. As the pressures in the flat jacks increased, the stress around the borehole also increased, possibly resulting in failure of the rock. The failure stress of the rock can then be determined from the borehole observations. Finally, the rock mass strength can be evaluated by increasing the flat jack pressure until gross failure of the tendon of rock between the flat jacks occurs. An additional variable for slot test #2 was the addition of heat from six heater boreholes drilled above and below the central borehole, in the tendon. Pressurizations were performed both prior to heating, and after the average temperature of the tendon had reached approximately 90°C. Because this test was conducted in a complex configuration, numerical modeling of the test is required during both test design and for post-test analyses of the results.

The as-built locations of the slots, platens, and borehole for slot test #2 are shown in Figures 21-23. Figure 21 shows a top view of the borehole and slots. A tendon of rock 123 cm wide was created by cutting two vertical slots in the rib. A 30.5-cm diameter, 179-cm deep borehole was centrally located between the slots, and was used to measure rock deformation. The slots were designed to be nominally 3.8cm wide, 200 cm deep and extend to a height of approximately 244 cm above the pre-cast invert. The as-built dimensions of the two slots are drawn to scale in Figures 22 and 23. The left slot was cut to a depth of 201 cm with respect to the axis of the borehole, and the right slot to a depth of 206 cm. Flat jacks with integral bearing plates for loading the rock tendon were placed in the slots. These flat jack platens were built to 91.4 cm (36 in.) on a side. The as-built dimensions are included in the scientific notebook for the pressurized slot tests, Pressurized Slot Testing for Determination of Rock Mass Modulus, Strength, and Thermal Expansivity of Tptpll Lithostratigraphic Unit, SN-SNL-SCI-027-V1.

The initial test site, selected by representatives of SNL and LANL Test Coordination Office, is located on the right rib at station 63+83 in the South Ramp. The 30.5cm diameter central hole and finished slots were evaluated for lithophysae content.

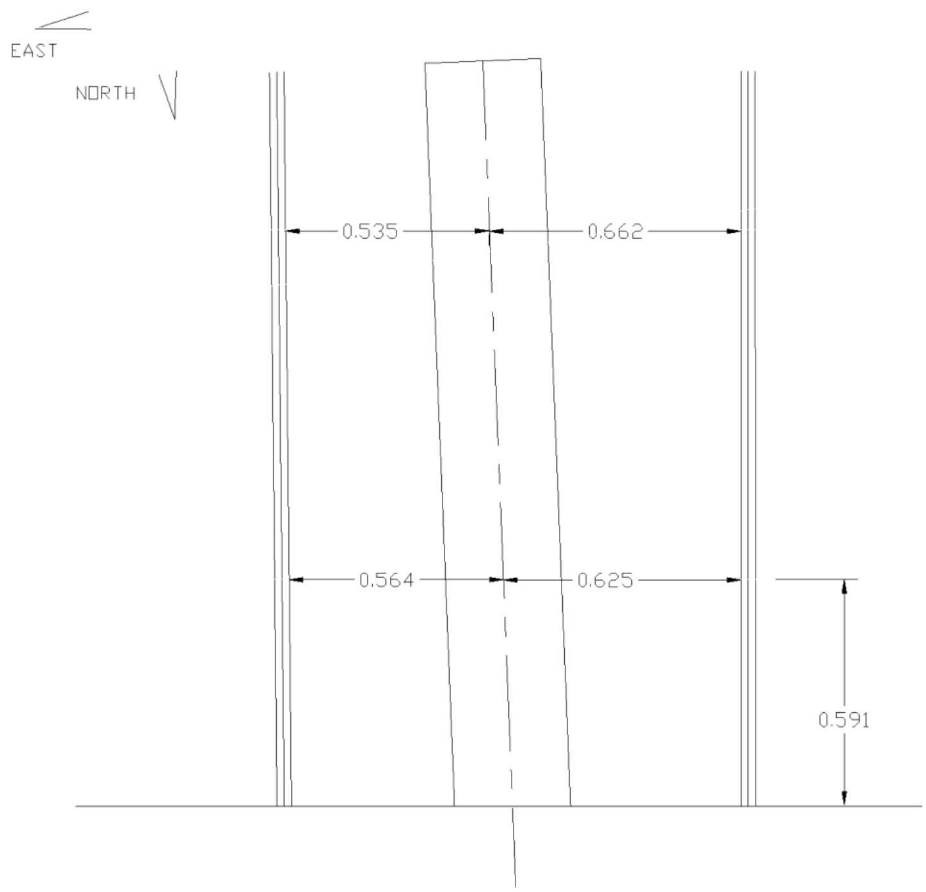


Figure 21. Platen Dimensions & Installation Locations for Left Slot 1/A & Right Slot 2/B, Slot Test #2

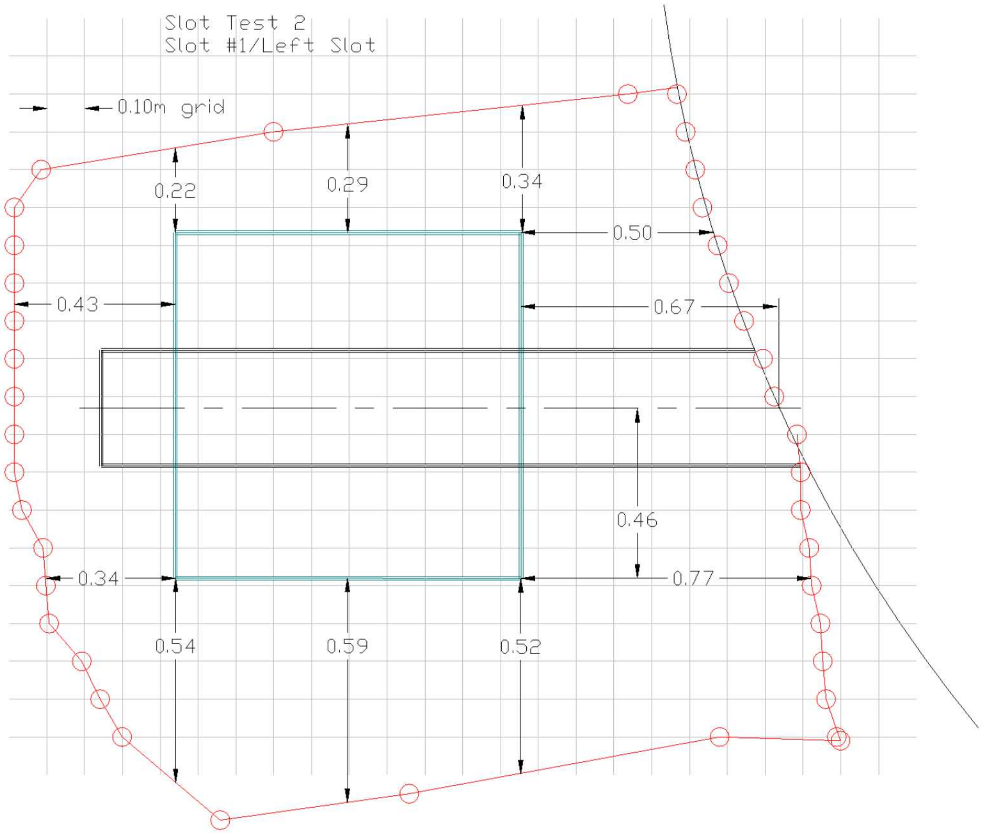


Figure 22. As-Built Dimensions of the Left Slot, Slot Test #2 (drawn on 0.1m grid)

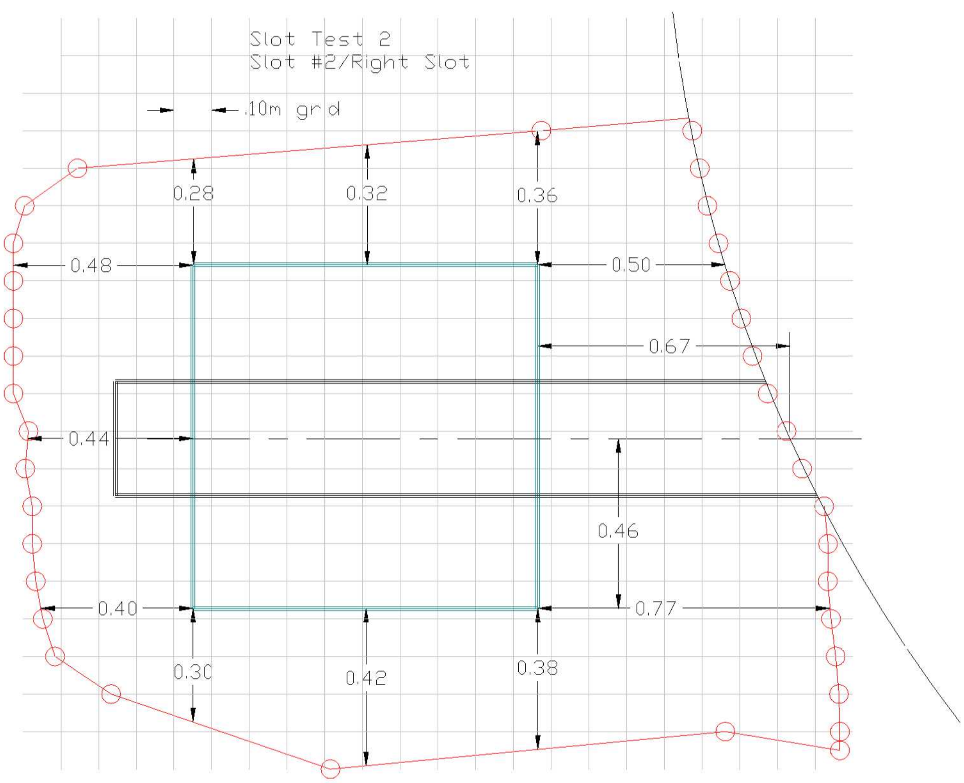


Figure 23. As-Built Dimensions of the Right Slot, Slot Test #2 (drawn on 0.1m grid)

Of the many displacement measurements collected for this test, the displacements within the central borehole are of primary interest. Six linear displacement transducer gages employing cantilevered strain gages were installed within the central borehole. The closure gages are numbered 1-6, and their location in the borehole with their xyz coordinates, are illustrated in Figure 24. Other displacement gages are located in the slots on the platens, and on the rib measuring horizontal and vertical displacements across the slots and tendons. A listing of these gages is included in Table 9.

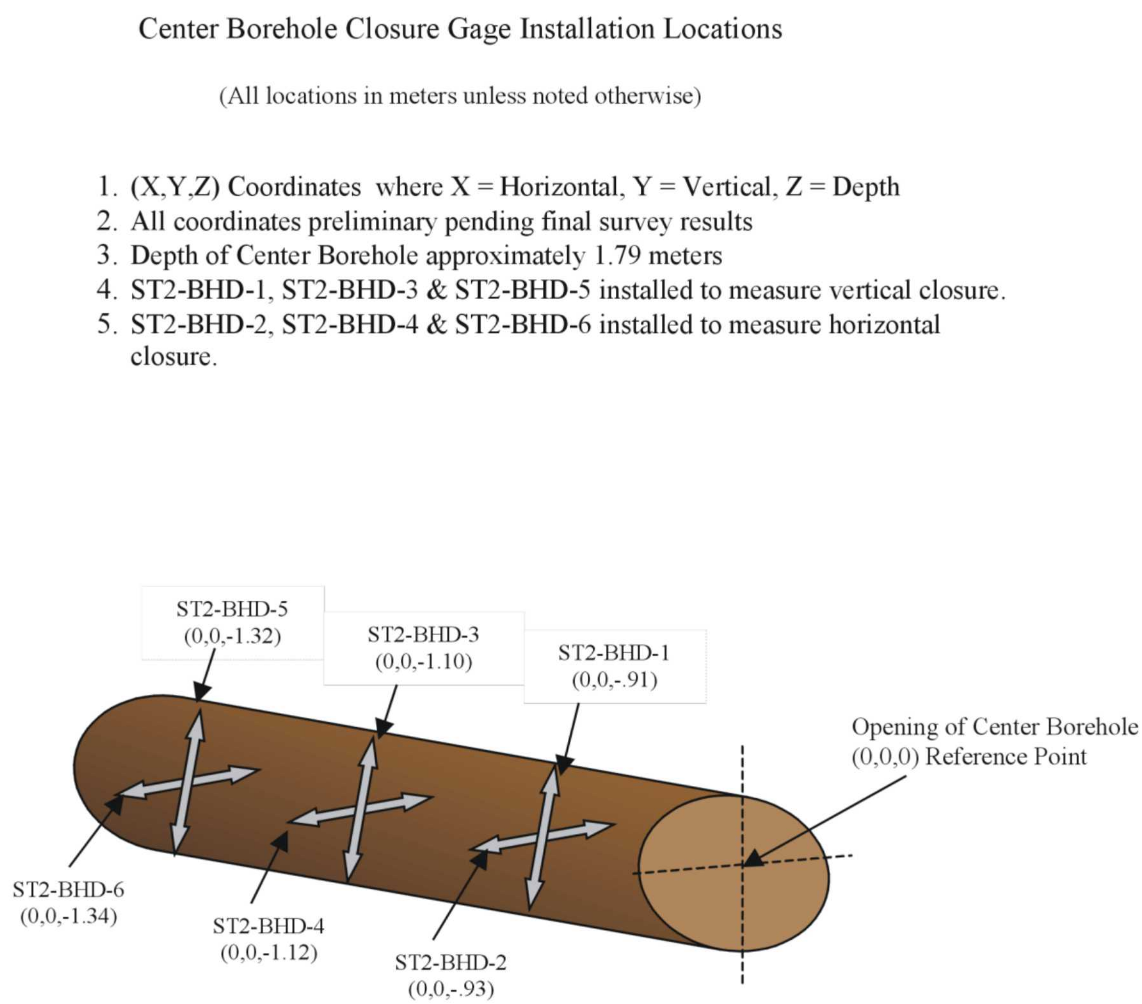


Figure 24. Center Borehole Closure Gage Installation Locations

The second pressurized slot test was performed in two stages. After the test was constructed, a pre-heat pressurization was performed on October 15, 2002. The heaters were then turned on, allowing the rock mass in the tendon to reach an average temperature of about 90°C. On October 30, 2002, two separate pressurizations took place. The first applied pressure to both slots. The second test, performed after the first pressurization had been relaxed, pressurized the left slot only until rock failure was observed. Only the first pressurization on 10/30/2002 was used to determine elastic rock mass properties.

Table 9. Slot Test #2 Displacement Gage Locations

Gage ID	Description
BHD gages are borehole displacement gages; #1, 3, and 5 measure vertical displacement; #2, 4, 6 measure horizontal displacement; positive displacement for compression	
ST2-BHD-1	Borehole; 20cm from leading edge of jack
ST2-BHD-2	Borehole; 20cm from leading edge of jack
ST2-BHD-3	Borehole; 41cm from leading edge of jack
ST2-BHD-4	Borehole; 41cm from leading edge of jack
ST2-BHD-5	Borehole; 61cm from leading edge of jack
ST2-BHD-6	Borehole; 61cm from leading edge of jack
LPD and RPD gages are platen displacement gages which measure horizontal displacement in the slots; positive displacement for extension	
ST2-LPD-1	Left upper front corner of employed platen
ST2-LPD-2	Left upper rear corner of employed platen
ST2-LPD-3	Left lower rear corner of employed platen
ST2-LPD-4	Left lower front corner of employed platen
ST2-RPD-1	Right upper front corner of employed platen
ST2-RPD-2	Right upper rear corner of employed platen
ST2-RPD-3	Right lower rear corner of employed platen
ST2-RPD-4	Right lower front corner of employed platen
RHD gages measure horizontal displacement at the rib; positive displacement for compression	
ST2-RHD-1	Left slot upper measurement pin set
ST2-RHD-2	Left slot middle measurement pin set
ST2-RHD-3	Left slot lower measurement pin set
ST2-RHD-4	Tendon upper measurement pin set
ST2-RHD-5	Tendon middle measurement pin set
ST2-RHD-6	Tendon lower measurement pin set
ST2-RHD-7	Right slot upper measurement pin set
ST2-RHD-8	Right slot middle measurement pin set
ST2-RHD-9	Right slot lower measurement pin set
RVD gages measure vertical displacement at the rib; positive displacement for compression	
ST2-RVD-1	Tendon next to left side of right slot
ST2-RVD-2	Tendon vertical mid-line
ST2-RVD-3	Tendon next to right side of left slot

5.2 TEST RESULTS

The rock quality at the test location for slot test #2 was better than for slot test #1. The rock was very porous and had numerous lithophysae in the test region. The most significant event not related to pressurization was the scaling of rock inside the borehole during the heating phase.

The pre-heat portion of the pressurized slot test #2 was performed on October 15, 2002. The pressure in the flat jacks was raised to a maximum of 520 psi (3.59 MPa) during the ~1.75-hour-long test. A time history of the average flat jack pressure, along with a fitted curve used as input to the calculations, is shown in Figure 25. The test's Principal Investigator noted no significant scaling of the rock in the borehole and on the drift wall surrounding the borehole during the pre-heat test. The closure measurements from inside the borehole are given in Figure 26. Positive displacement in this case means closure, and negative means expansion. The horizontal gages (gages 2, 4, and 6) are closing during the test, and the vertical gages (1, 3, and 5) are expanding. Note that the front gages (1 and 2) exhibit higher displacements than the middle gages (3 and 4), and more so than the back gages (5 and 6).

The heated portion of the pressurized slot test #2 was performed on October 30, 2002. The pressure in the flat jacks was raised to a maximum of 1554 psi (10.72 MPa) during the ~3-hour-long test. A time history of the average flat jack pressure, along with a fitted curve used as input to the calculations, is shown in Figure 27. The second spike some time after the main test was performed on the left slot only, and was not included in this analysis. The test's Principal Investigator noted some visible signs on compression failure of the rock in the borehole and on the drift wall surrounding the borehole during the heated test. The closure measurements from inside the borehole are given in Figure 28. As in the pre-heat test, the horizontal gages are closing during the test, and the vertical gages are expanding. The heated test is different from the pre-heat in two significant ways. One, note that the middle horizontal gage (BHD-4) exhibits the highest displacement. Two, there is a large amount of offset in the displacements once the pressure is released, particularly for the middle gages. This is an indication that some compressive failure may have begun during this pressurization; the slot and tendon data show this potential failure more dramatically.

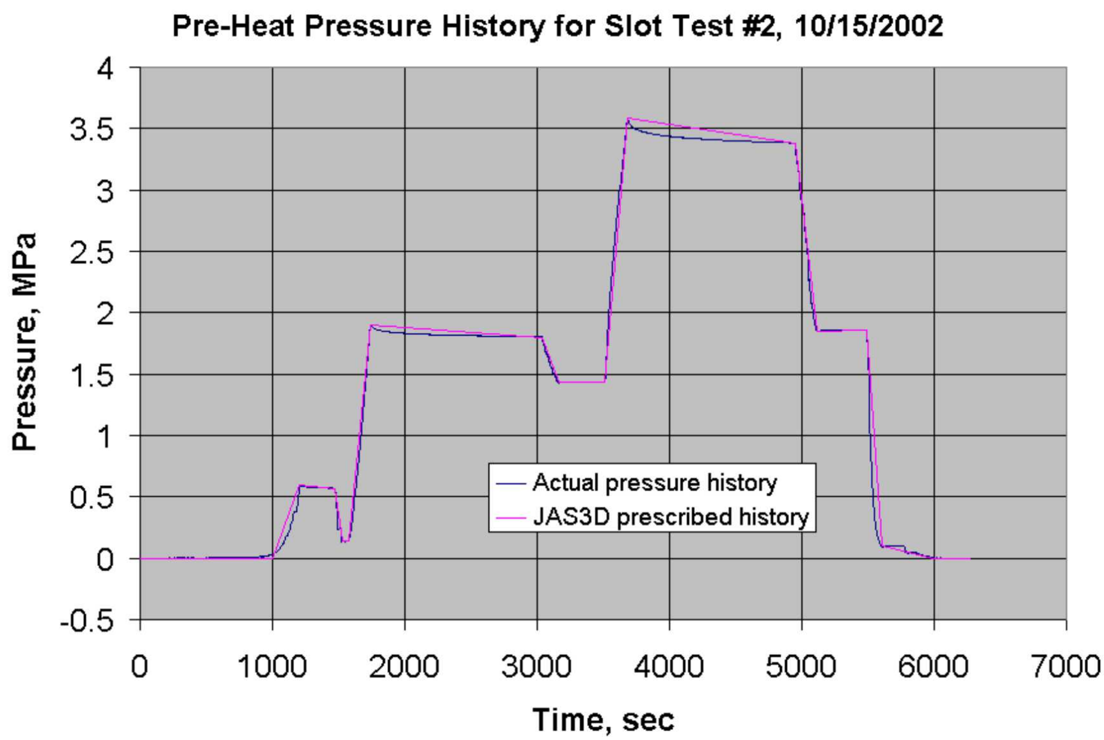


Figure 25. Pre-Heating Flat Jack Pressure History for Slot Test #2 (DTN SN0212F4102102.003)

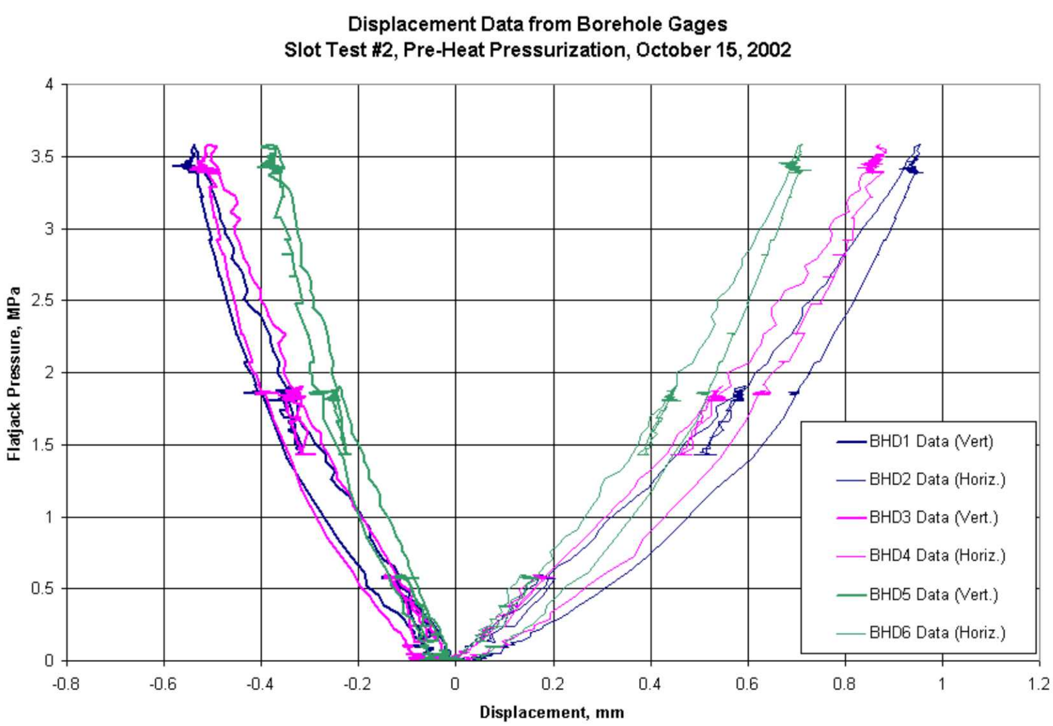


Figure 26. Closure Data from the Central Borehole, Slot Test #2, Pre-Heat Test (DTN SN0212F4102102.003)

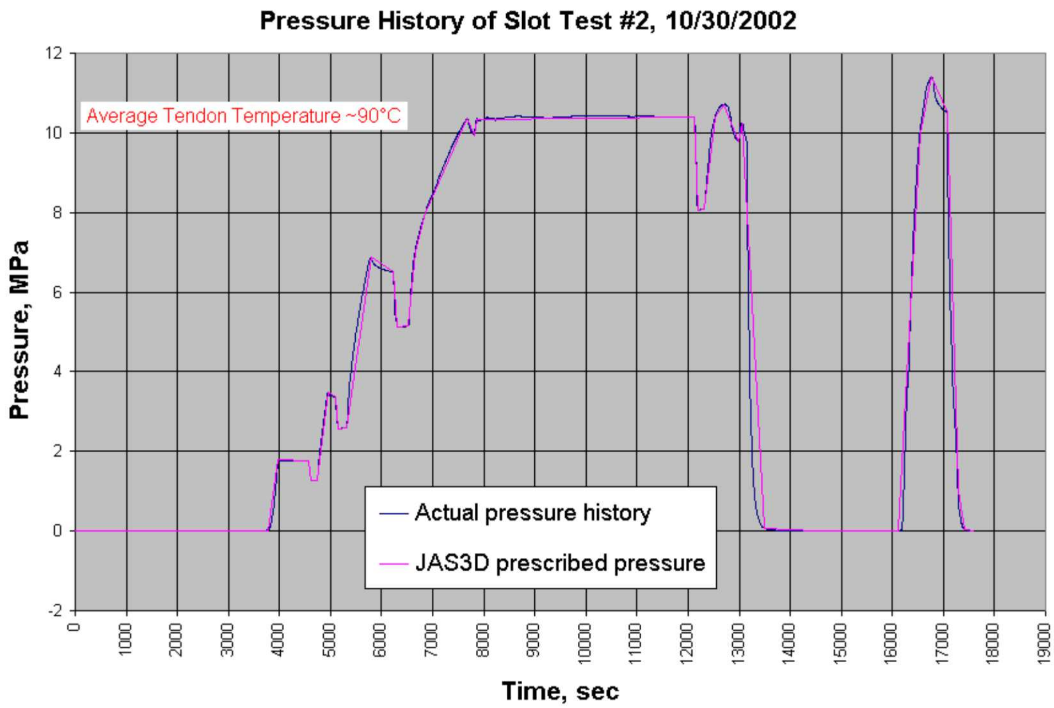


Figure 27. Flat Jack Pressure History for Slot Test #2 (Heated Test) (DTN SN0212F4102102.003)

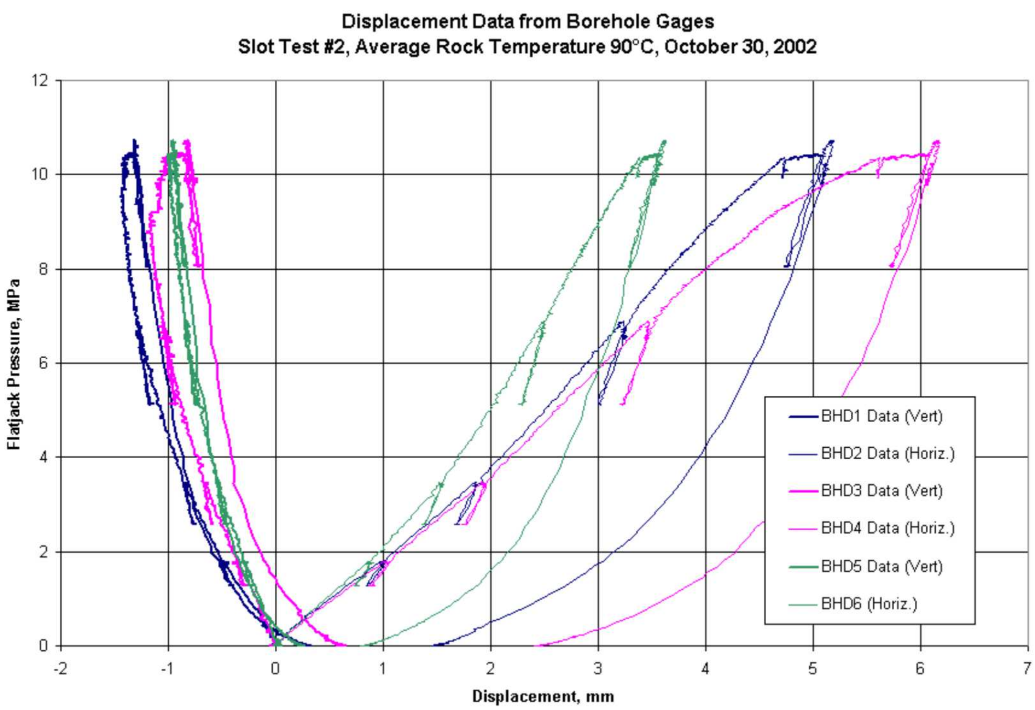


Figure 28. Closure Data from the Central Borehole, Slot Test #2, Heated Test (DTN SN0212F4102102.003)

5.3 ANALYTICAL PROCEDURE

Two types of analyses were performed to derive the rock mass modulus and Poisson's ratio for this test. First, a Kirsch solution was used to estimate elastic constants. From this solution, initial estimates of elastic modulus of 2.0 GPa and Poisson's ratio of 0.20 were estimated for the pre-heat test. The value of 0.20 was very similar to the Poisson's ratio value obtained for Tptpll from the first pressurized slot test conducted in May 2002, and with the laboratory value of 0.24 obtained from Tptpul intact rock samples (SNL, 2002e). The modulus value differed significantly from the intact rock value of 15.5 GPa obtained from Busted Butte samples (Price et al., 1985), as well as the same laboratory samples conducted this summer for Tptpul samples (ambient dry 13.7 GPa; heated dry 10.8 GPa; ambient saturated 5.9 GPa). This difference indicates the decrease in quality of the in situ rock due to the ubiquitous presence of fractures and lithophysae.

The estimates from the Kirsch solution were used as input to the second analytical method, which was ultimately used to derive the values presented here. This analysis was performed using the finite element code JAS3D. An additional code was written to map the measured temperatures onto the computational mesh. The code, called test2temps.f, is a FORTRAN-77 code written to read the temperature data from a file, and along with other assumptions made about the temperatures with the rock mass, interpolated temperature values on the computational mesh at selected time steps. Thermocouples were located on the rib surface, in the borehole, and in the slots. Thermocouples were also located in the heater boreholes, but these did not give reliable readings of the temperatures there. The temperatures in the heater boreholes were assumed to range from 120-180°C, based on location and time during the test and observations related by the principal investigators. The code is a one-time-use code, and will not be submitted to YMP Software QA management. A copy of the source code is included in the technical review package for this analysis, as well as the records package for this data submittal.

A summary of the parameters required for the performance of the JAS3D calculations is shown in Table 10. A mesh was generated using the as-built dimensions of the South Ramp drift, slots, borehole, and flat jack and closure gage locations. The selected material model was the elastic model, to determine the deformational character of the in situ rock as a rock mass. For this analysis, no lithophysae were inserted into the mesh; this is consistent with an elastic rock mass problem definition. Initial stress conditions were taken from measurements made elsewhere in the ESF. The problem definition called for the excavation of the slots and borehole to allow for stress relief, the application of the flat jack pressurization for the pre-heat test, the application of the heat, and finally the pressurizations during the heating phase.

Table 10. Input Parameters for Analysis of Pressurized Slot Test #2

Parameter		**Info (Source DTN, Version number, etc.)**
Analysis code	JAS3D	Version 1.6.F, Software Tracking Number 10023-1.6-00; qualified per procedure AP-SI.1Q, Rev. 3/ICN 4, Software Management; completed qualification on 7/17/2002, re-installed on local network 8/2/2002.
Code to interpolate temperature data to computational mesh	test2temps.f	FORTRAN-77 code to read temperature data, interpolate to mesh at selected times; source code included with technical review/records packages
Material model	Elastic (compliant joint model was also used)	No lithophysae in mesh
Thermal expansion coefficients for Tptpul	Range from 6.9-25.5 microstrains/°C for the given temperature range	SNL, 2001b
Slot/flat jack location, geometry coordinate values	See Figures 21, 22, 23, and 24	Scientific Notebook, Pressurized Slot Testing for Determination of Rock Mass Modulus, Strength, and Thermal Expansivity of Tptpll Lithostratigraphic Unit, SN-SNL-SCI-027-V1
Initial stresses	Vertical: σ_v = 4.3 MPa Horizontal: σ_H = 3.0 MPa (parallel to Drift) σ_h = 2.0 MPa (parallel to borehole)	SNL (2000); values from Alcove 6, located at ESF Station 37+37
Dry Bulk Density of Host Rock	1910 kg/m^3	Price et al. (1985), based on lab tests on samples collected from Tptpll unit from Busted Butte outcrop
Poisson's ratio	0.20	Initial guess based on value obtained from analysis of Slot Test #1 (SNL, 2002b)
Flat jack loading conditions	See Figures 25, 27	Slot Test #2 Data (SNL, 2002c)
Test temperature, pressure, and displacement data	See Figures 26, 28, etc.	Slot Test #2 Data (SNL, 2002c)

5.4 COMPARISON OF DATA TO ANALYSES

Figures 29-32 compare the pre-heat pressurization data to JAS3D predictions using different values for elastic modulus. Two different models were run for the preheat predictions: a purely elastic model was run with several values for elastic modulus and Poisson's ratio; and a compliant joint model (CJM) with a set of horizontal fractures. The reason the compliant joint model was exercised was to try to better match the displacements in the vertical borehole gages. The presence of horizontal fractures would allow more freedom of movement in the vertical direction in response to the horizontal load supplied by the flat jacks.

Based on the elastic model, a value for Young's modulus in the range of 2.0-3.0 GPa, along with a Poisson's ration value of 0.20, match the horizontal borehole displacement data fairly well. These values were also obtained by a Kirsch solution of the test setup. Predictions for values of Young's modulus closer to 3.0 GPa give better predictions for the horizontal gages, whereas values closer to 2.0 GPa are better for the vertical gages. When values in this range were applied to the compliant joint model, the vertical displacement data were matched much more closely than with the elastic model. This is but one of many indications from the test data that the rock mass exercised by this slot test does not behave in an elastic manner. There is also evidence of compressive failure in much of the test data, particularly during the pressurization after the rock has been heated.

The preheat horizontal displacements measured in the tendon are also compared to the elastic model with E=3.0 GPa, and the compliant joint model with E=2.5 GPa. The predictions from these values tend to bound the data well. Based on these analyses, the recommended values of elastic modulus E and Poisson's ratio ν for preheated temperature conditions are 3 GPa and 0.2, respectively. The determination of this value is based on a fitting of the slope of the predicted pressure-displacement curve to the loading portion of the data (the secant modulus).

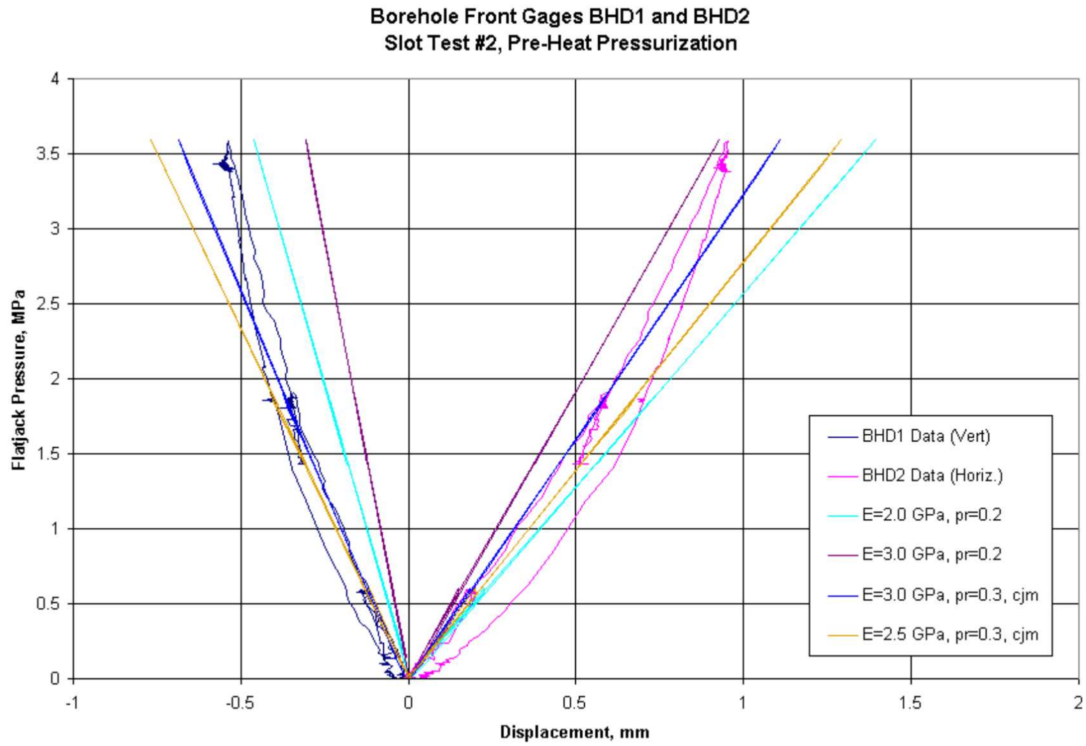


Figure 29. Displacements in Borehole Gages #1 and 2, Pre-Heat Test, Data vs. Predictions (DTN SN0212F4102102.003)

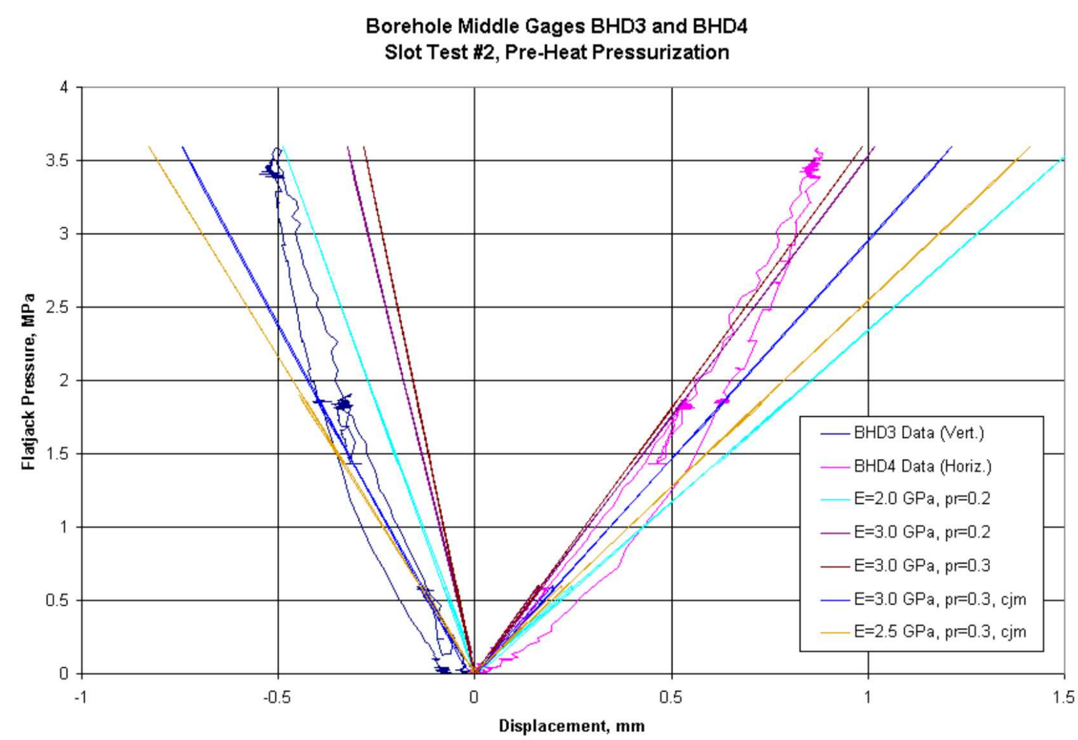


Figure 30. Displacements in Borehole Gages #3 and 4, Pre-Heat Test, Data vs. Predictions (DTN SN0212F4102102.003)

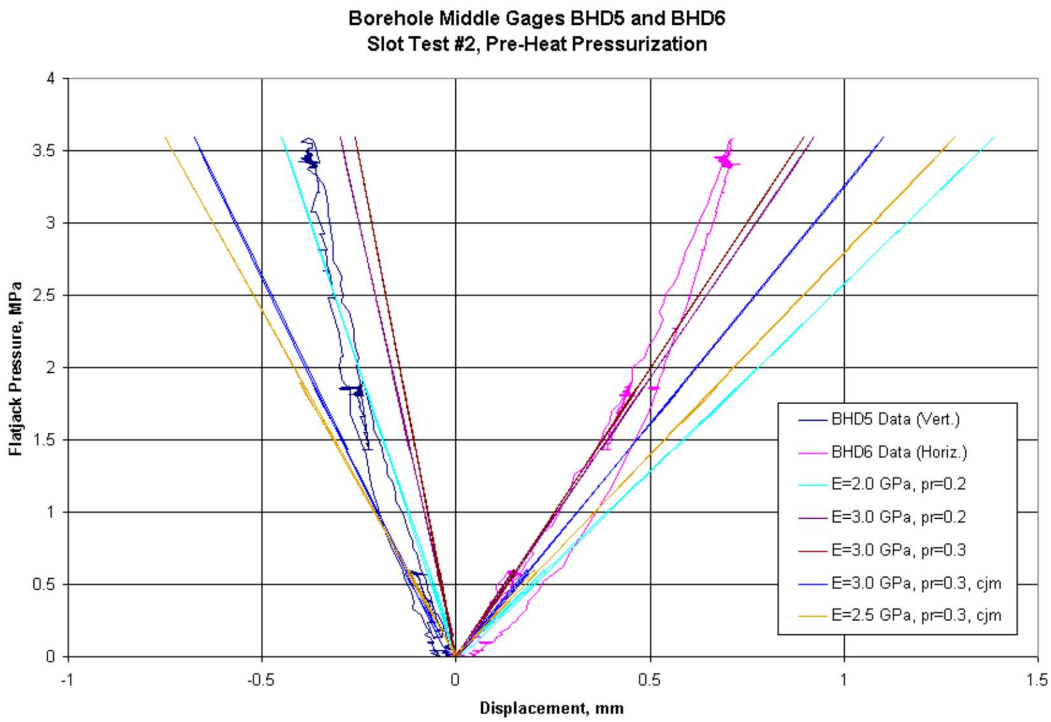


Figure 31. Displacements in Borehole Gages #5 and 6, Pre-Heat Test, Data vs. Predictions(DTN SN0212F4102102.003)

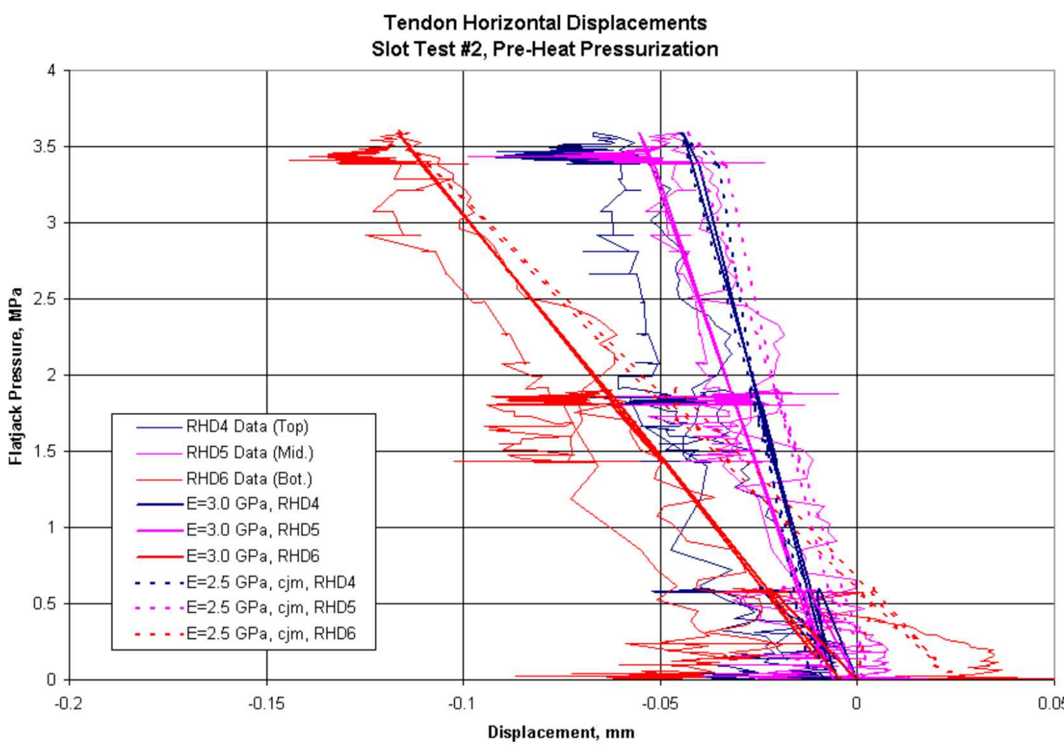


Figure 32. Horizontal Displacements in the Tendon, Pre-Heat Test, Data vs. Predictions (DTN SN0212F4102102.003)

The results from the heated pressurization indicate that the preheat pressurization and/or the heat input have had some effect on the overall rock mass mechanical properties. Figures 33-35 compare the borehole displacements to elastic analyses using values for Young's modulus of 1.0, 2.0, and 3.0 GPa. For the front and middle borehole gages, a Young's modulus value of 1.8 GPa would probably be appropriate. Note also that the elastic analyses are now matching the data better for the vertical gages, which is a possible indication that fractures and/or pore space was inelastically compressed by the earlier test. Also note that the second test reached a higher pressure than the preheat test, and that the borehole gages maintain a fairly linear change during the loading portion of the test. However, the unloading portion of the test exhibits a slope corresponding to a Young's modulus of about 4 GPa, and have undergone a permanent displacement of between 1-2.5 mm.

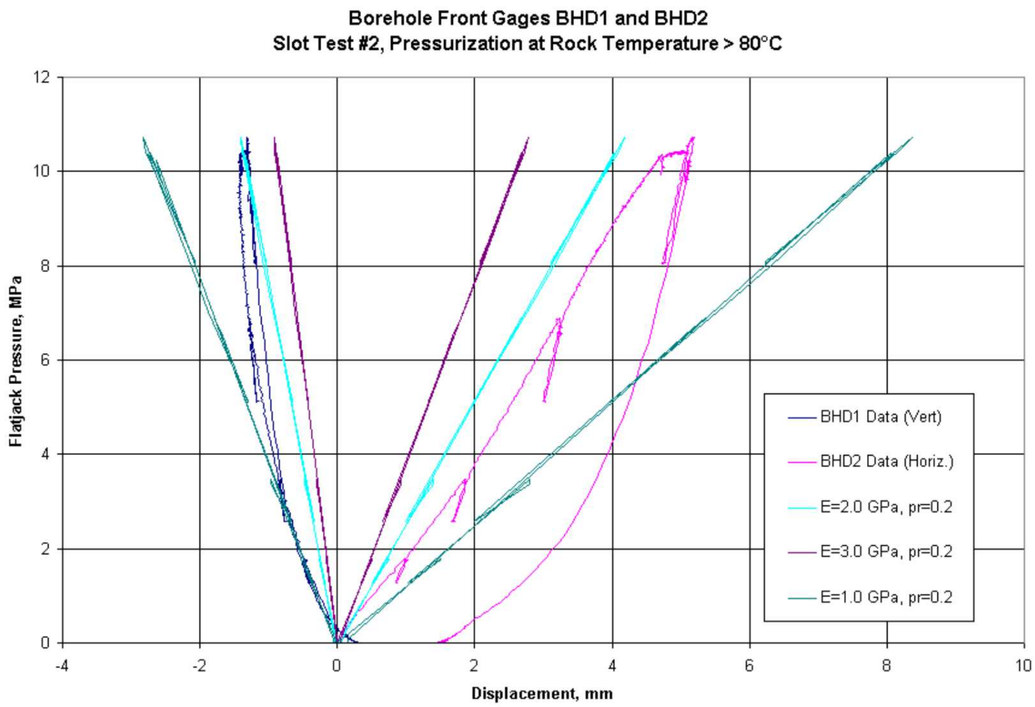


Figure 33. Displacements in Borehole Gages #1 and 2, Heated Test, Data vs. Predictions (DTN SN0212F4102102.003)

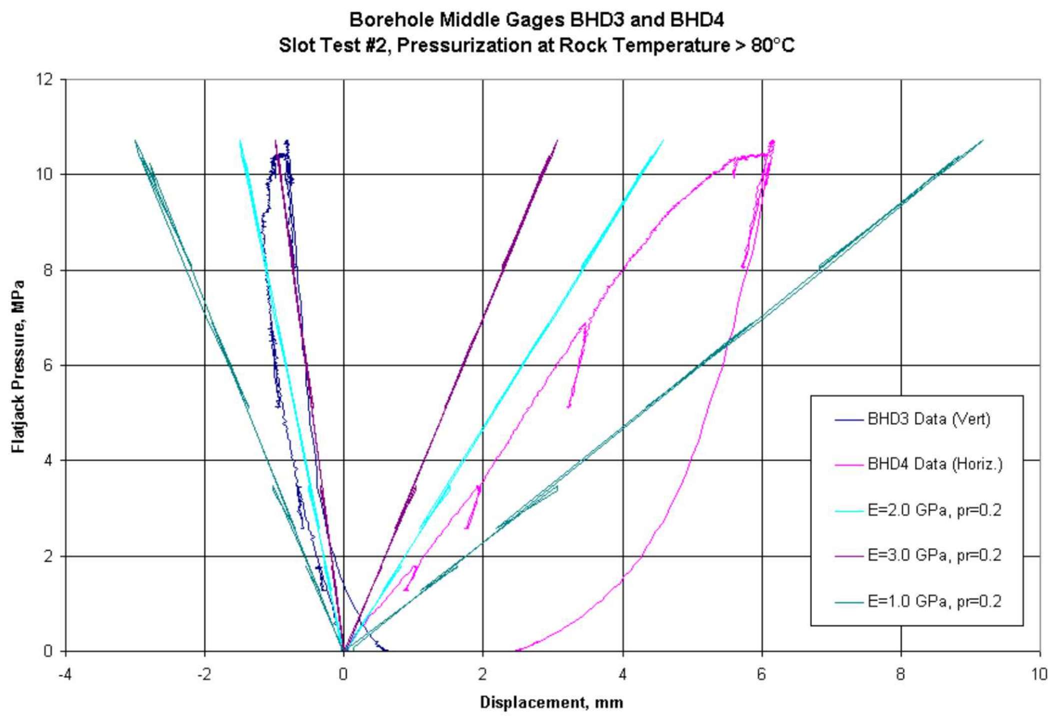


Figure 34. Displacements in Borehole Gages #3 and 4, Heated Test, Data vs. Predictions (DTN SN0212F4102102.003)

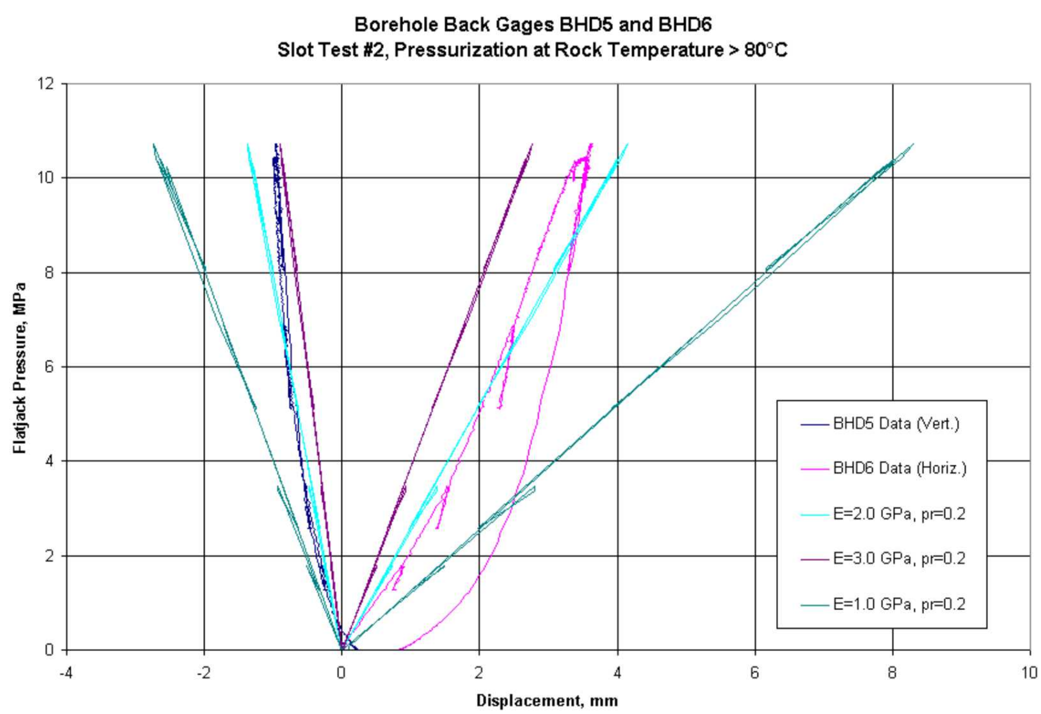


Figure 35. Displacements in Borehole Gages #5 and 6, Heated Test, Data vs. Predictions (DTN SN0212F4102102.003)

Figure 36 shows the displacements on the rib across the left slot (positive indicates compression). The plot indicates that the characteristic Young's modulus for the early part of the test is about 2.0 GPa. However, at a flat jack pressure starting at about 5 MPa, the slot data indicates the beginning of compressive failure of the rock surrounding the slot, with the displacements at the rib turning from extensive to compressive. When the flat jack pressure is held at a value above 10 MPa, the rock continues to yield, causing the slot opening at the rib to close. A similar response is noted for the tendon horizontal displacements shown in the Figure 37. The tendon also undergoes extension during the lower pressures, indicating that at the rib surface, the entire tendon area is being elongated. This flaring out of the tendon and slots at the rib surface may be due to the low modulus and strength of the rock. Again, starting at a flat jack pressure of about 4 MPa, the tendon behavior changes significantly, with a precipitous increase in extension, contrasting with the compression of the slots at the surface. There is also a significant failure of rock to the right of the right slot at a pressure of about 8 MPa; the yielding exhibited by the slot and tendon gages at a constant pressure of about 10 MPa is probably related to this rock failure. The tendon response during the elastic regime is best matched by a Young's modulus value of 1.0 GPa. Thus, values of Young's modulus of 1-2 GPa are appropriate for heated conditions; an average value of 1.5 GPa can be used for ground support analyses. Based on the analyses conducted for slot test #2, the recommended values of Young's modulus and Poisson's ration for average rock temperatures of about 90°C are 1.50 GPa ±0.50 GPa and 0.2, respectively, with the caveat that rock compressive failure was noticed at flat jack pressures as low as 4 MPa.

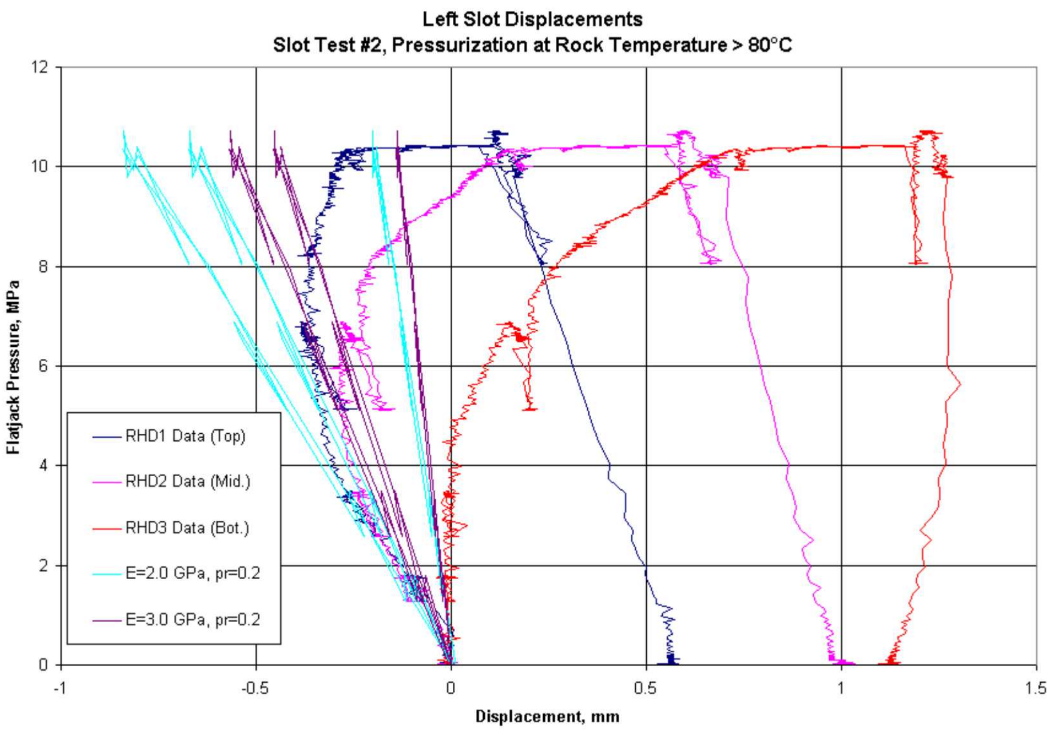


Figure 36. Displacements Across the Left Slot, Heated Test, Data vs. Predictions (DTN SN0212F4102102.003)

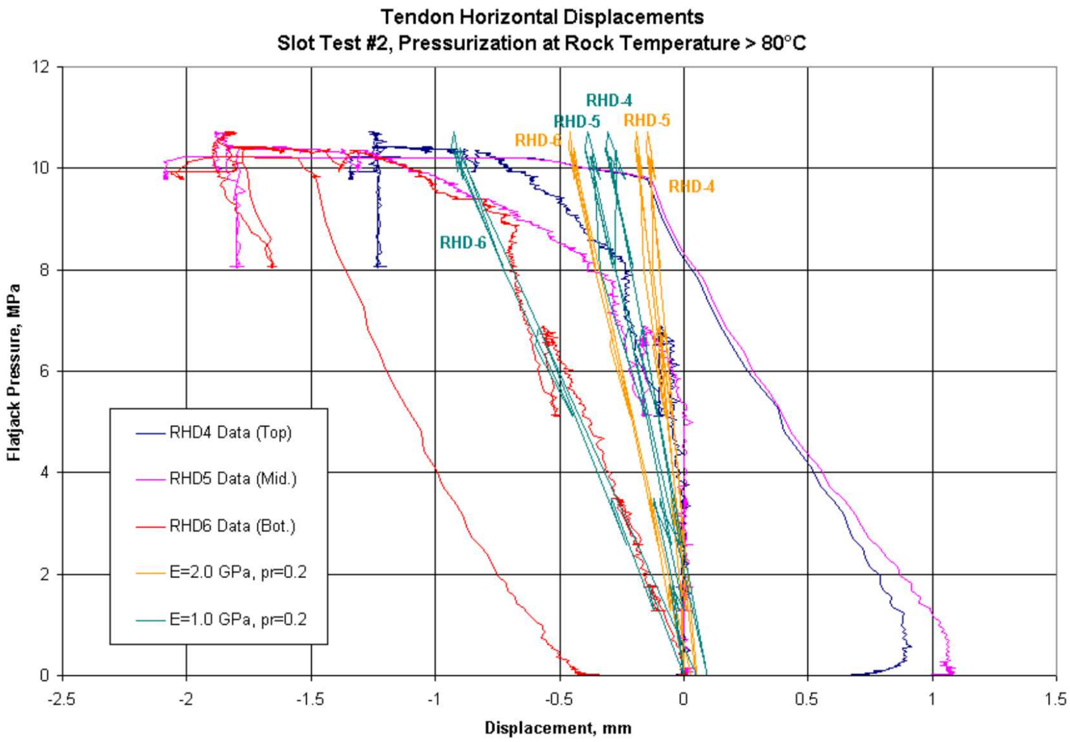


Figure 37. Displacements Across the Tendon, Heated Test, Data vs. Predictions (DTN SN0212F4102102.003)

5.5 CONCLUSIONS

The second pressurized slot test, which was conducted in the Topopah Springs upper lithophysal unit, produced data that can be used, along with numerical analyses, to obtain rock mass values for mechanical properties such as deformation modulus and Poisson's ratio. Using JAS3D, a mechanical code qualified under YMP QA procedures, the following properties were derived: for ambient temperature conditions, rock mass modulus = 3.0 GPa ±0.5 GPa, and Poisson's ratio = 0.20; and for rock temperature of about 90°C, rock mass modulus = 1.5 GPa ±0.5 GPa, and Poisson's ratio = 0.20. These values are specific to the location of the test. The reduced rock mass modulus at the higher temperature indicates that some rock failure occurred during the heating process, which created fractures and deformed existing lithophysae and pore space to allow greater displacement during pressurization. The rock mass quality at the test site was somewhat poor due to the presence of fractures and large lithophysae, although the quality was noticeably better than at the site for slot test #1.

6. SLOT TEST #3

This data report describes the displacement data obtained from Pressurized Slot Test #3, as well as the procedure used for calculating rock mass mechanical properties (rock mass modulus and Poisson's ratio) from the measurements. This slot test was conducted in the Enhanced Characterization of the Repository Block (ECRB) Drift of the Exploratory Studies Facility (ESF) at station 21+25, in the Topopah Springs lower lithophysal unit Tptpll. The data here were developed by comparison of numerical model predictions for displacements with the measured displacements from the actual test. The measured displacements and pressures from Slot Test #3 were obtained under Supplement V controls from the scientific notebook for the pressurized slot tests, Pressurized Slot Testing for Determination of Rock Mass Modulus, Strength, and Thermal Expansivity of Tptpll Lithostratigraphic Unit, SN-SNL-SCI-027-V1. The test data were submitted to the YMP TDMS (SNL, 2003a), as well as the developed rock mass mechanical properties data (SNL, 2003b). The developed data that were submitted to the TDMS are presented in Table 11. The deviation values indicated for the elastic moduli are to be taken as approximations only, based on the ranges of values used in the numerical analyses.

Table 11. Data Submittals for the Pressurized Slot Test #3, 12/10/2002 (SNL, 2003b)

Data Descriptor	**Data Value**
Slot Test Location	ECRB Station 21+25, vertical borehole in the Tptpll unit
Rock Mass Elastic Modulus, ambient conditions, GPa	1.0 GPa ±0.3 GPa
Poisson's Ratio	0.33

This report documents the analysis performed to develop the rock mass mechanical properties. For such documentation, the following subjects will be discussed:

- A brief discussion of the test setup.
- A brief discussion of the test results.
- A discussion of the analytical procedure and input parameters.
- Presentation of results and rationale for selection of the rock mass mechanical property values.

6.1 TEST SETUP

The nominal test layout for the slot tests is shown in Figure 3. For the previous two slot tests, these slots were cut into the rib of the drift. However, for Slot Test #3, the slots and borehole were cut into the floor of the drift. The remainder of the test set-up was much like the previous two tests. The as-built locations of the slots, platens, and borehole for slot test #3 are shown in Figures 38-40. Figure 38 shows a top and a side view of the borehole and slots. A tendon of rock 121 cm wide was created by cutting two vertical slots in the rib. A 30.5-cm diameter, 183-cm deep borehole was centrally located between the slots, and was used to measure rock deformation. The slots were designed to be nominally 3.8cm wide and 150 cm deep. The as-built dimensions of the two slots are drawn to scale in Figures 39 and 40. The left slot was cut to a depth of 154 cm with respect to the axis of the borehole, and the right slot to a depth of 149 cm.

Flat jacks with integral bearing plates for loading the rock tendon were placed in the slots. These flat jack platens were built to 91.4 cm (36 in.) on a side. The as-built dimensions are included in the scientific notebook for the pressurized slot tests, Pressurized Slot Testing for Determination of Rock Mass Modulus, Strength, and Thermal Expansivity of Tptpll Lithostratigraphic Unit, SN-SNL-SCI-027-V1.

The initial test site, selected by representatives of SNL and the LANL Test Coordination Office, is located on the right rib at station 21+25 in the ECRB. The 30.5cm diameter central hole and finished slots were evaluated for lithophysae content.

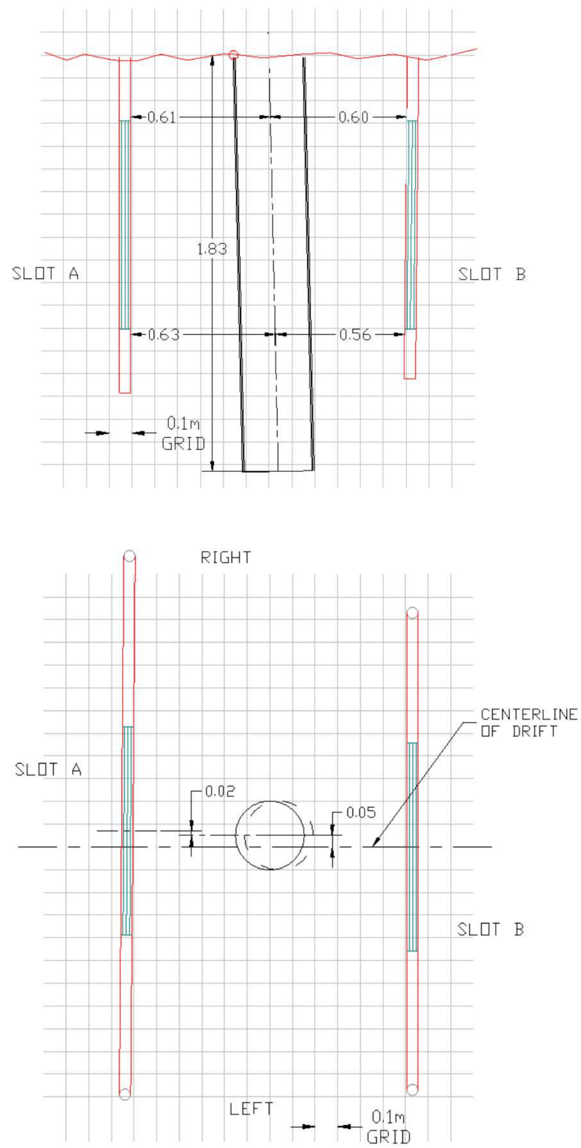


Figure 38. Platen Dimensions & Installation Locations for Left Slot 1/A & Right Slot 2/B, Slot Test #3

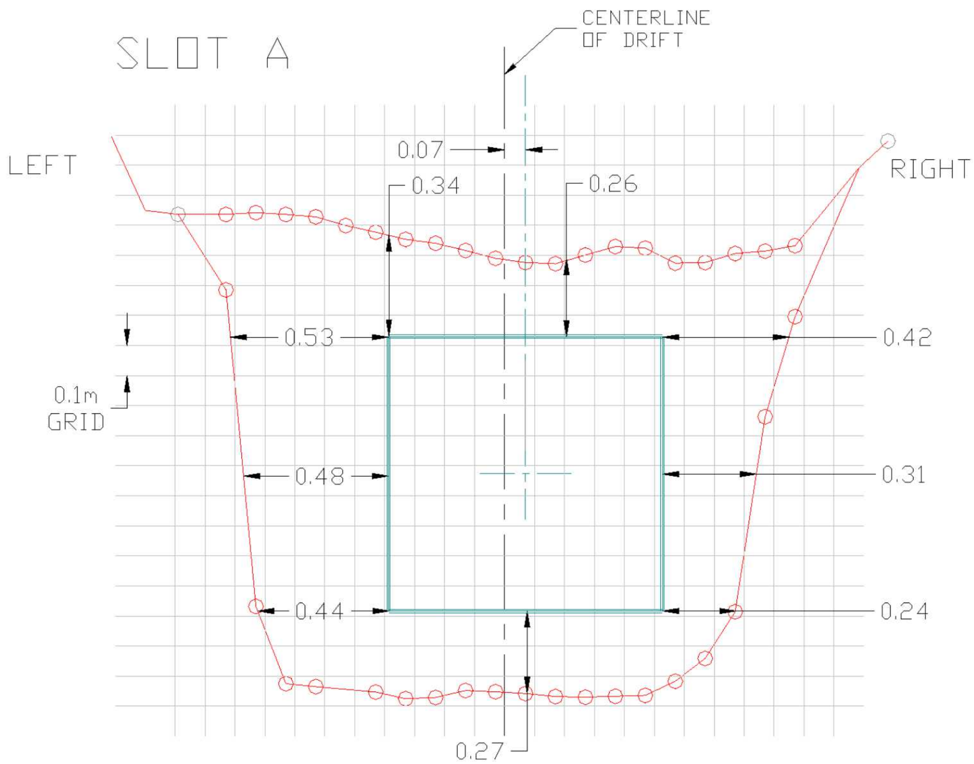


Figure 39. As-Built Dimensions of the Left Slot, Slot Test #3 (drawn on 0.1m grid)

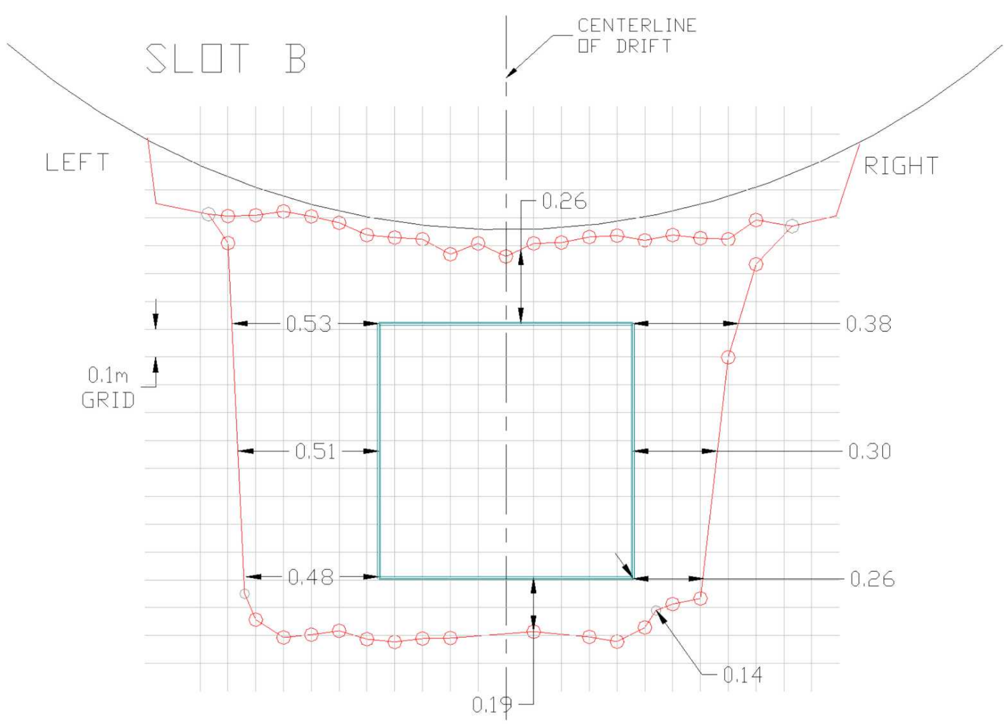


Figure 40. As-Built Dimensions of the Right Slot, Slot Test #3 (drawn on 0.1m grid)

Of the many displacement measurements collected for this test, the displacements within the central borehole are of primary interest. Six linear displacement transducer gages employing cantilevered strain gages were installed within the central borehole. The closure gages are numbered 1-6, and their location in the borehole with their xyz coordinates, are illustrated in Figure 41. Other displacement gages are located in the slots on the platens, and on the rib measuring horizontal displacements both parallel and perpendicular to the drift across the slots and tendons. A listing of these gages is included in Table 12. (Note: The previous slot tests were installed in the rib of the drift, whereas slot test #3 was installed in the floor of the drift. The gage nomenclature was assigned to the same corresponding gages as for the previous tests. Therefore, some of the figures may refer to "horizontal" and "vertical" displacements, which is in keeping with the setup for slot tests #1 and #2. For slot test #3, "horizontal" means horizontal displacement parallel to the drift, and thus also parallel to the direction of the applied pressure; "vertical" means horizontal displacement perpendicular to the drift and to the direction of applied pressure.)

Center Borehole Closure Gage Installation Locations

(All locations in meters unless noted otherwise)

1. **(X,Y,Z) Coordinates where X = Horizontal-ECRB Axis, Y = Vertical, Z =** Horizontal-across drift
2. All coordinates preliminary pending final survey results
3. Depth of Center Borehole approximately 1.79 meters
4. ST3-BHD-1, ST3-BHD-3 & ST3-BHD-5 installed to measure cross-drift closure.
5. ST3-BHD-2, ST3-BHD-4 & ST3-BHD-6 installed to measure ECRB-axis closure.

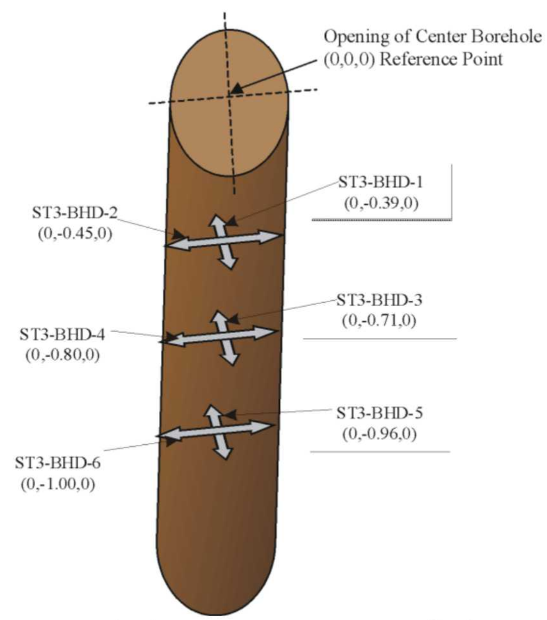


Figure 41. Center Borehole Closure Gage Installation Locations

Table 12. Slot Test #3 Displacement Gage Locations

Gage ID	Description
BHD gages are borehole displacement gages; #1, 3, and 5 measure horizontal displacement perpendicular to drift; #2, 4, 6 measure horizontal displacement parallel to drift; positive displacement for compression	
ST3-BHD-1	Borehole; 5cm from leading edge of jack
ST3-BHD-2	Borehole; 11cm from leading edge of jack
ST3-BHD-3	Borehole; 37cm from leading edge of jack
ST3-BHD-4	Borehole; 46cm from leading edge of jack
ST3-BHD-5	Borehole; 62cm from leading edge of jack
ST3-BHD-6	Borehole; 66cm from leading edge of jack (malfunctioned during the test)
LPD and RPD gages are platen displacement gages which measure horizontal displacement in the slots; positive displacement for extension	
ST3-LPD-1	Left upper front corner of employed platen
ST3-LPD-2	Left upper rear corner of employed platen
ST3-LPD-3	Left lower rear corner of employed platen
ST3-LPD-4	Left lower front corner of employed platen
ST3-RPD-1	Right upper front corner of employed platen
ST3-RPD-2	Right upper rear corner of employed platen
ST3-RPD-3	Right lower rear corner of employed platen
ST3-RPD-4	Right lower front corner of employed platen
RHD gages measure horizontal displacement parallel to the drift at the rib; positive displacement for compression	
ST3-RHD-1	Left slot upper measurement pin set
ST3-RHD-2	Left slot middle measurement pin set
ST3-RHD-3	Left slot lower measurement pin set
ST3-RHD-4	Tendon upper measurement pin set
ST3-RHD-5	Tendon middle measurement pin set
ST3-RHD-6	Tendon lower measurement pin set
ST3-RHD-7	Right slot upper measurement pin set
ST3-RHD-8	Right slot middle measurement pin set
ST3-RHD-9	Right slot lower measurement pin set
RVD gages measure "vertical" displacement at the rib (for this test, horizontal displacement perpendicular to the drift); positive displacement for compression	
ST3-RVD-1	Tendon next to left side of right slot
ST3-RVD-2	Tendon vertical mid-line
ST3-RVD-3	Tendon next to right side of left slot

6.2 TEST RESULTS

The third pressurized slot test was performed on December 10, 2002. The rock quality at the test location for slot test #3 was similar to that for slot test #1, with many noticeable fractures within the tendon. The rock was very porous and had numerous lithophysae in the test region. The pressure in the flat jacks was raised to a maximum of 987 psi (6.8 MPa) during the ~4-hour-long test. A time history of the average flat jack pressure, along with a fitted curve used as input to the calculations, is shown in Figure 42.

The closure measurements from inside the borehole are given in Figure 43. Positive displacement in this case means closure, and negative means expansion. The "horizontal" gages (gages 2 and 4; gage 6 malfunctioned during the test) are closing during the test, and the "vertical" gages (1, 3, and 5) are expanding. Note that the middle gages (3 and 4) exhibit higher displacements than the front gages (1 and 2), and more so than the back gages (5). Two significant features can be observed from the borehole data. The first feature is a shift in the displacement data observed at a pressure of about 0.69 MPa (100 psi), during the initial pressure build-up period. The shift represents an unrecoverable change in displacement, as evidenced by data later on during the test. This shift in data was likely to a slip along one of the predominant fractures in the test area, possibly the one traversing near the borehole. All the borehole and rib gages (BHD, RHD, and RVD) show this slippage behavior, at levels ranging from 0.36 to 0.53 mm. The platen gages (LPD, RPD) were unaffected by this slippage.

The second phenomenon is exhibited by the large deviation from elastic behavior beginning at flat jack pressures around 5 MPa (725 psi). Around this time, the test's Principal Investigators noted visible signs of compression failure of the rock in the borehole collar and the drift invert surrounding the borehole during the test. There was significant fracturing and vertical movement of rock on the floor, as well as substantial rock fall into the borehole. The slot and tendon data show this failure more dramatically. Only the displacement-pressure data up to the apparent failure point should be used to determine a rock mass modulus value; beyond that point, the rock behaved in an inelastic manner characterized by some combination of fracturing, scaling, and lithophysae compression.

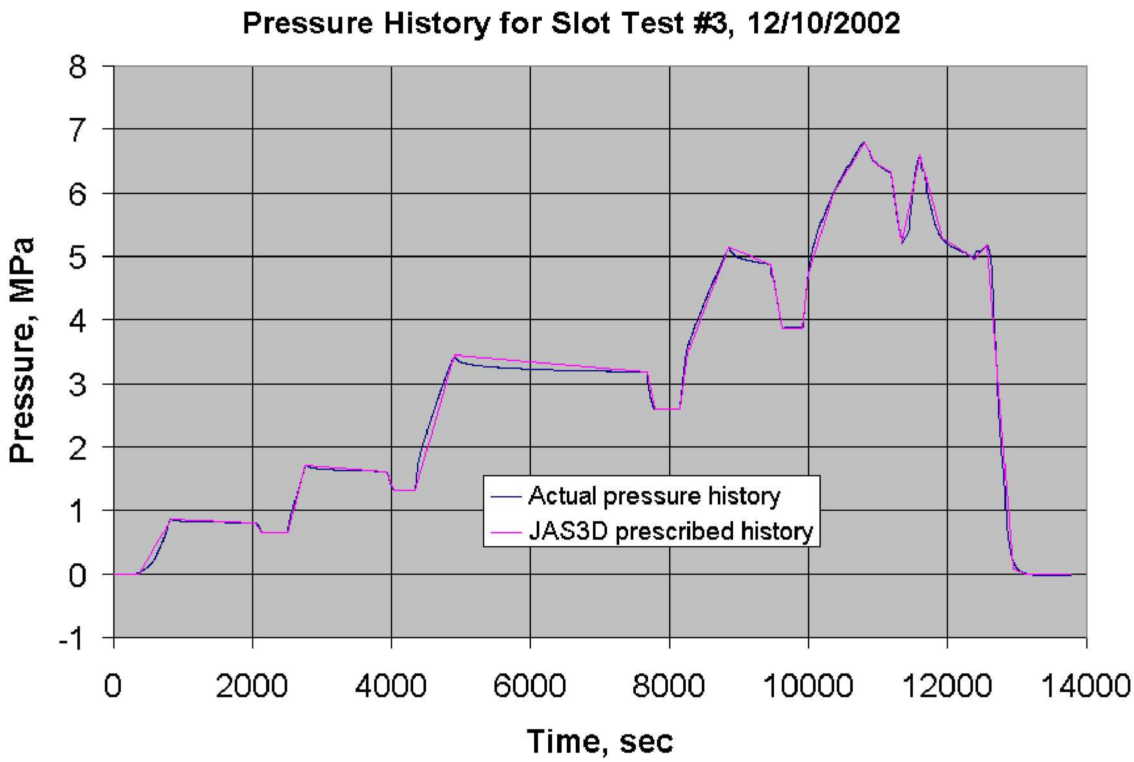


Figure 42. Flat jack Pressure History for Slot Test #3 (DTN SN0301F4102102.005)

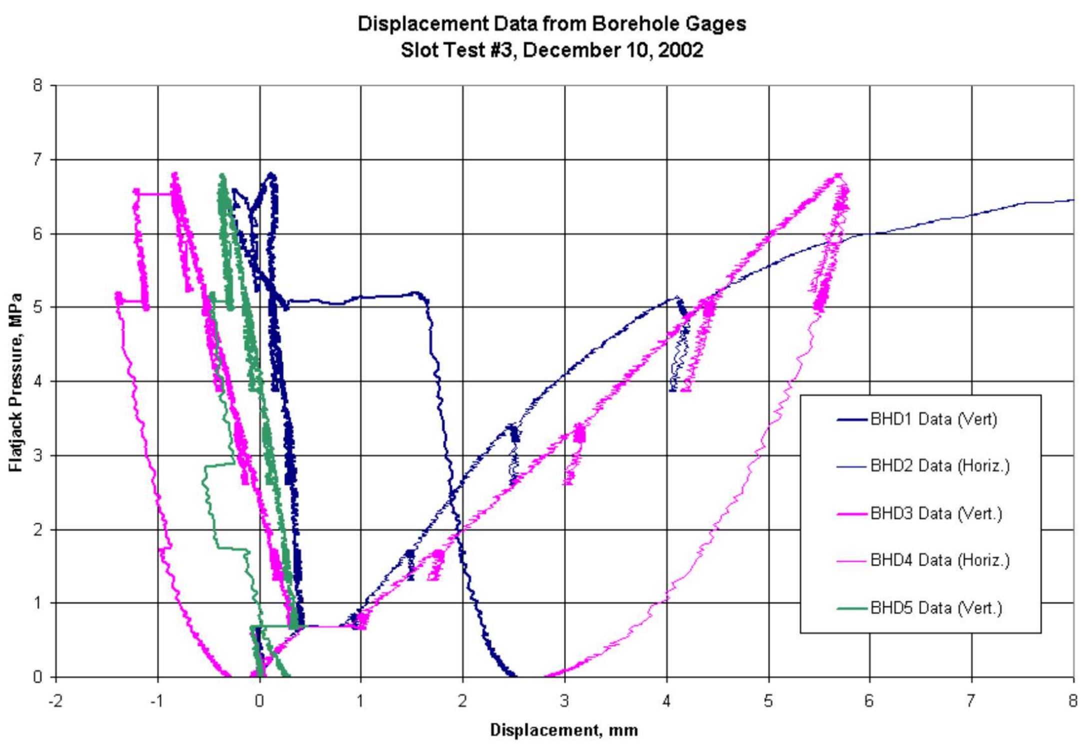


Figure 43. Closure Data from the Central Borehole, Slot Test #3 (DTN SN0301F4102102.005)

6.3 ANALYTICAL PROCEDURE

A mechanical stress analysis utilizing appropriate initial stress and boundary conditions, as-built test geometry, and an appropriate material model, is required in order to derive rock mass mechanical properties from the test data. Two types of analyses were performed to derive the rock mass modulus and Poisson's ratio for this test. First, a Kirsch solution was used to estimate elastic constants. From this solution, initial estimates of elastic modulus of 0.69 GPa and Poisson's ratio of 0.33 were estimated for the test. The Poisson's ratio value of 0.33 was quite different from the value of 0.20 obtained for Tptpll/Tptpul from the first two pressurized slot tests conducted in May and October 2002, and with the laboratory value of 0.24 obtained from Tptpul intact rock samples (SNL, 2002e). The modulus value differed significantly from the intact rock value of 15.5 GPa obtained from Busted Butte samples (Price et al., 1985), as well as the same laboratory samples conducted this summer for Tptpul samples (ambient dry 13.7 GPa; heated dry 10.8 GPa; ambient saturated 5.9 GPa). This difference indicates the decrease in quality of the in situ rock due to the ubiquitous presence of fractures and lithophysae.

The estimates from the Kirsch solution were used as input to the second analytical method, which was ultimately used to derive the values presented here. This analysis was performed using the finite element code JAS3D. A summary of the parameters required for the performance of the JAS3D calculations is shown in Table 13. A mesh was generated using the as-built dimensions of the ECRB drift, slots, borehole, and flat jack and closure gage locations. The selected material model was the elastic model, to determine the deformational character of the in situ rock as a rock mass. For this analysis, no lithophysae were inserted into the mesh; this is consistent with an elastic rock mass problem definition. Initial stress conditions were taken from measurements made elsewhere in the ESF. The problem definition called for the excavation of the slots and borehole to allow for stress relief, and the application of the flat jack pressurization for test.

6.4 COMPARISON OF DATA TO ANALYSES

Figures 44-46 compare the pressurization data from the borehole displacement gages to JAS3D predictions using different values for elastic modulus and Poisson's ratio. The predicted displacements from the JAS3D simulations were adjusted by the magnitude of the shift each gage encountered as described earlier. The predictions using a value for elastic modulus of 1.0 GPa, along with a Poisson's ration value of 0.33, match the "horizontal" borehole displacement data from gages BHD2 and BHD4 very well, as well as the data from "vertical" gage BHD3. The data from gages BHD1 and BHD5 would suggest the use of a higher value for either elastic modulus or Poisson's ratio. However, the excellent matches for both horizontal gages, and for the middle vertical gage nearest to the center of pressure application, strongly justify these values. The value of elastic modulus of 1.0 GPa was somewhat higher than the value of 0.69 GPa obtained by the Kirsch solution of the test setup. Values for modulus from the Kirsch solution and the JAS3D solution agreed more closely for the previous two slot tests.

Table 13. Input Parameters for Analysis of Pressurized Slot Test #3

Parameter		**Info (Source DTN, Version number, etc.)**
Analysis code	JAS3D	Version 1.6.F, Software Tracking Number 10023-1.6-00; qualified per procedure AP-SI.1Q, Rev. 3/ICN 4, Software Management; completed qualification on 7/17/2002, re-installed on local network 8/2/2002.
Material model	Elastic	No lithophysae in mesh
Slot/flat jack location, geometry coordinate values	See Figures 38, 39, 40, 41	Scientific Notebook, Pressurized Slot Testing for Determination of Rock Mass Modulus, Strength, and Thermal Expansivity of Tptpll Lithostratigraphic Unit, SN-SNL-SCI-027-V1
Initial stresses	Vertical: σ_v = 4.3 MPa Horizontal: σ_H = 3.0 MPa (parallel to ESF) σ_h = 2.0 MPa (perpendicular to ESF)	SNL (2000); values from Alcove 6, located at ESF Station 37+37 (Slot orientation was approximately 52° from principal stress orientation.)
Dry Bulk Density of Host Rock	1910 kg/m^3	Price et al. (1985), based on lab tests on samples collected from Tptpll unit from Busted Butte outcrop
Poisson's ratio	0.33	Initial guess based on value obtained from Kirsch analysis of Slot Test #3
Flat jack loading conditions	See Figure 42	Slot Test #3 data (SNL, 2003a)
Test pressure and displacement data	See Figure 43	Slot Test #3 data (SNL, 2003a)

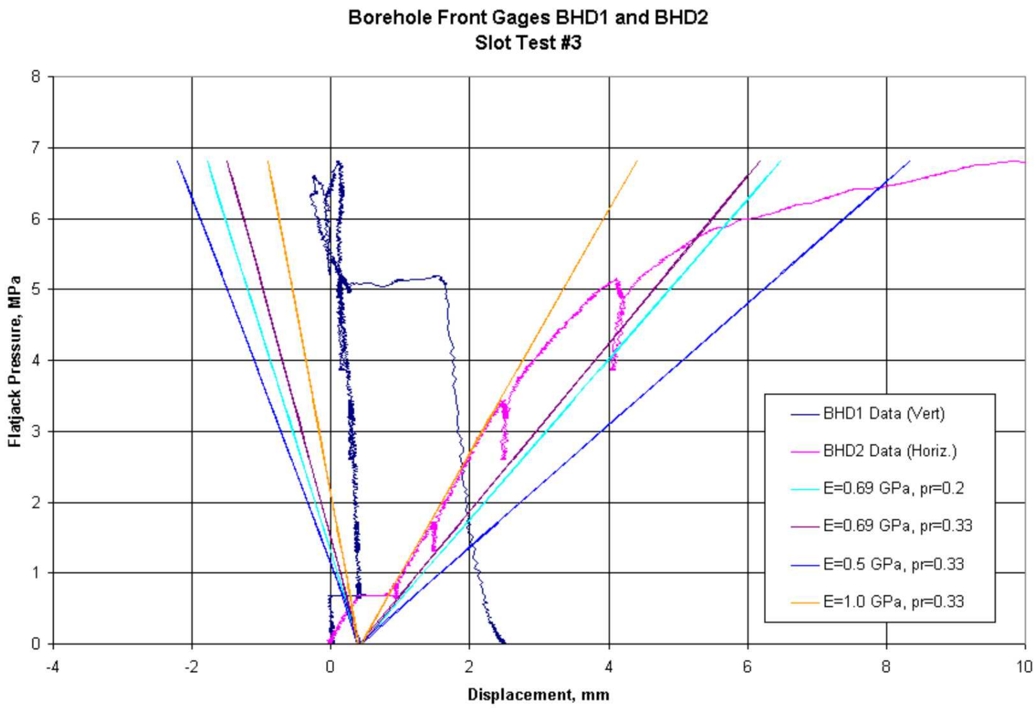


Figure 44. Displacements in Borehole Gages #1 and 2, Data vs. Predictions (DTN SN0301F4102102.005)

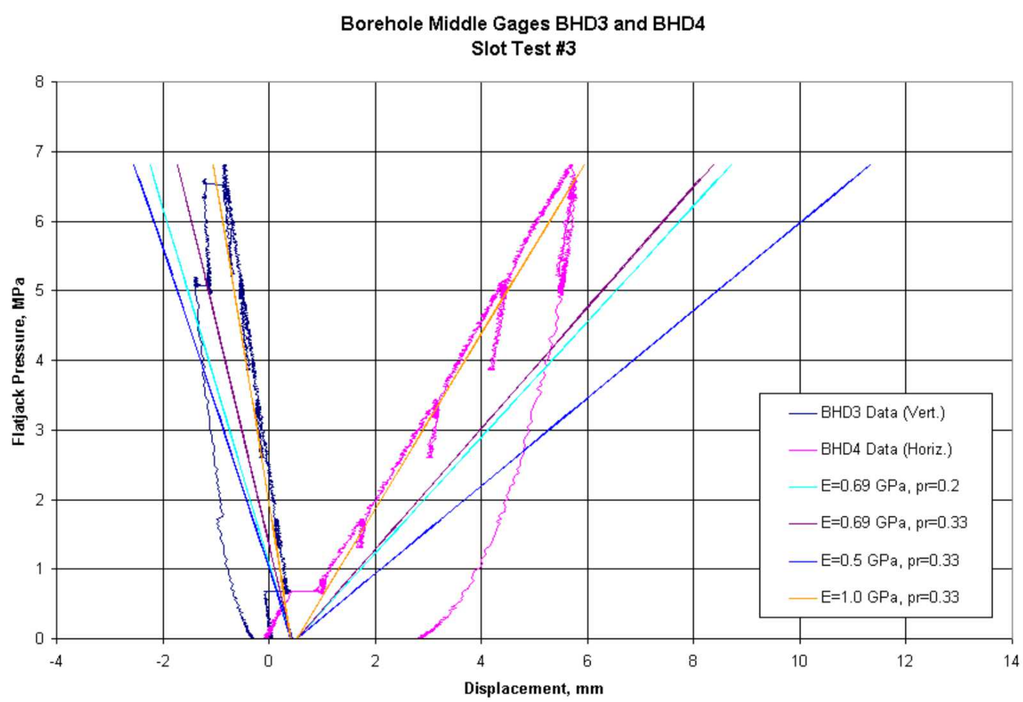


Figure 45. Displacements in Borehole Gages #3 and 4, Data vs. Predictions (DTN SN0301F4102102.005)

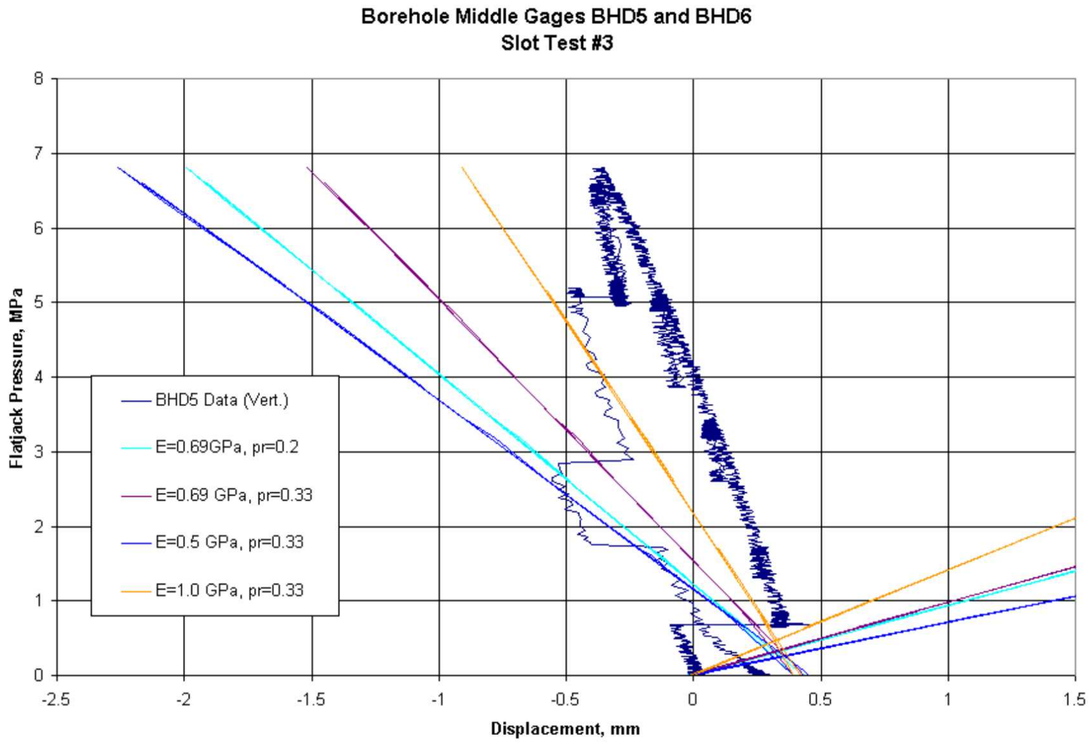


Figure 46. Displacements in Borehole Gages #5 and 6, Data vs. Predictions (DTN SN0301F4102102.005)

Figures 47 and 48 show horizontal displacements parallel to the drift at the rib surface. Figure 47 shows these displacements across the left slot. Note that the slope of the measured pressure-displacement curve is much steeper than the predictions, and that inelastic behavior begins at pressures near 5 MPa. Figure 48 shows the same displacement in the tendon, and the predicted and measured behaviors are strikingly different. Whereas the predictions show the tendon at the rib compressing with increasing pressure, the data indicate the opposite effect - an immediate and comparatively large extension. This behavior, which was so aptly described by one of the Principal Investigators as being "like squeezing a marshmallow", indicates the rock near the rib is highly enough fractured and/or contains significant lithophysal space to render it completely inelastic from the outset of the test. The significant vertical rock movement and fracture creation observed by the PIs during the test further support this conclusion.

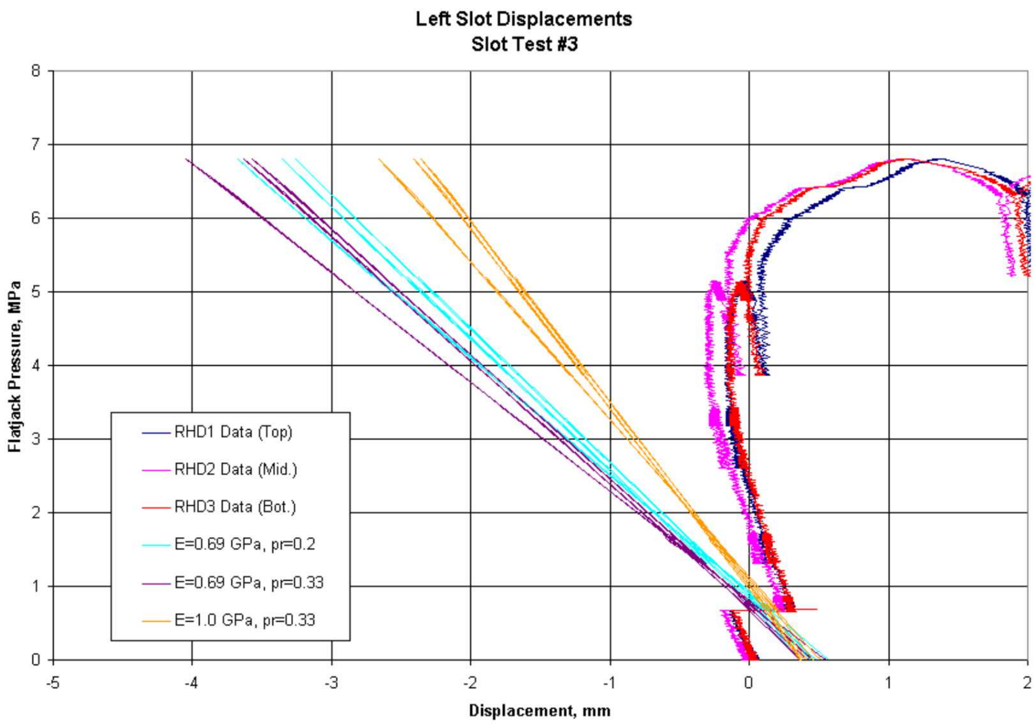


Figure 47. Horizontal Displacements Across the Left Slot, Data vs. Predictions (DTN SN0301F4102102.005)

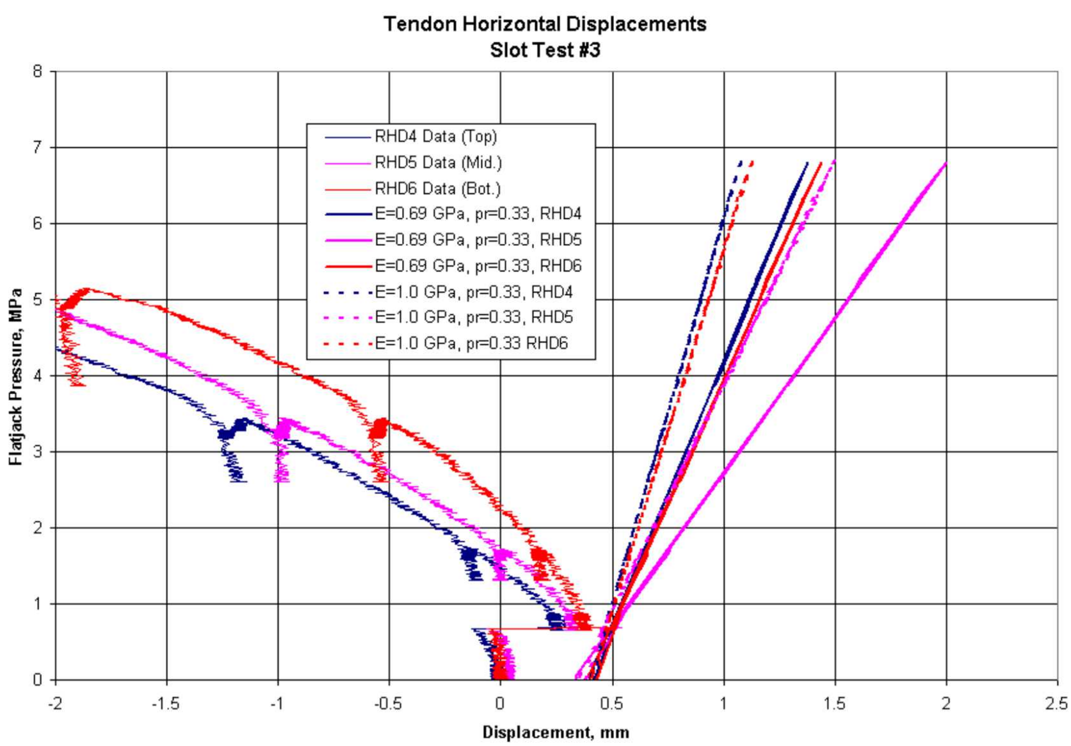


Figure 48. Horizontal Displacements in the Tendon, Data vs. Predictions (DTN SN0301F4102102.005)

6.5 CONCLUSIONS

The third pressurized slot test, which was conducted in the Topopah Springs lower lithophysal unit, produced data that can be used, along with numerical analyses, to obtain rock mass values for mechanical properties such as deformation modulus and Poisson's ratio. Using JAS3D, a mechanical code qualified under YMP QA procedures, the following properties were derived for ambient temperature conditions: rock mass modulus = 1.0 GPa ±0.3 GPa, and Poisson's ratio = 0.33. These values are specific to the location of the test. The deviation value for elastic modulus, ±0.3 GPa, is an approximation based on the difference between the result predicted by the numerical analyses and also by the Kirsch solution. The rock mass quality at the test site was somewhat poor due to the presence of fractures and large lithophysae. Further numerical investigation of the three slot tests using non-elastic models (cap models, inclusion of lithophysal spaces, joint models, etc.) is encouraged due to the non-linear behavior exhibited by most of the gages on these tests.

7. ADDITIONAL POST-TEST ANALYSIS

Besides for the determination of rock mass elastic modulus values, the slot tests performed in the ESF provide a wealth of information about the host rock. Much of this information can be used in the repository design process. Two post-test analyses of the slot tests are discussed in this section. The first analysis of the thermal expansion attempts to explain why the laboratory value for the thermal expansion coefficient predicted displacements far less than those actually measured. The second analysis examines rock failure observed during heating and pressurization. It uses the numerical results from the JAS3D calculations to estimate rock strength values based on observations of when rock failure began, and the stresses in the rock at those locations and times. A shear failure profile for each test location was developed from these analyses.

7.1 THERMAL EXPANSION DURING HEATING PHASE, SLOT TEST #2

For the second pressurized slot test, which was conducted in the Topopah Springs upper lithophysal unit, the in situ rock was heated for a period of 15 days prior to the pressurized slot test. The heating was performed to obtain rock mass values for mechanical properties such as deformation modulus and Poisson's ratio at different temperatures. During the heating period, rock deformation due to thermal expansion was monitored by the various displacement gages described in Chapter 5. Also, prior to the onset of heating for slot test #2, laboratory measurements of thermal expansion coefficients were taken using Tptpul samples from the test region (SNL, 2001b). The thermal expansion coefficient ranged from 6.9-25.5 microstrains/°C for the given temperature range; these coefficients are detailed in Table 14.

Table 14. Thermal Expansion Coefficient developed from lab data for Tptpul (SNL, 2001b)

Low temperature, °C	High temperature	Thermal Expansion Coefficient (μstrains/°C)
25	50	6.9
50	75	8.6
75	100	9.7
100	125	15.7
125	150	18.4
150	175	21.7
175	200	25.5

Predictive calculations of the rock deformation due to thermal expansion were performed using JAS3D using the thermal expansion coefficients listed in Table 14 and an approximate three-dimensional temperature history based on thermocouple measurements. Also, the original analysis assumed elastic rock behavior using the ambient-temperature mechanical properties of rock mass modulus = 3.0 GPa ±0.5 GPa, and Poisson's ratio = 0.20 described in Chapter 5. The resulting predicted displacements were significantly less than those measured in the in situ test block. Figures 49, 50, and 51 show the measured and predicted displacements measured for the borehole closure gages BHD1-BHD6. The behavior of primary interest is that after fifty hours, when the temperatures have reached a nearly steady state. Other displacement gages exhibited similar differences between measured and predicted behavior.

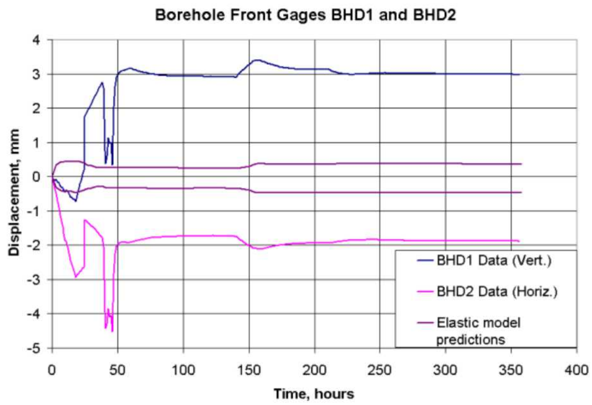


Figure 49: Thermal Expansion Measured at Borehole Gages BHD1 and BHD2

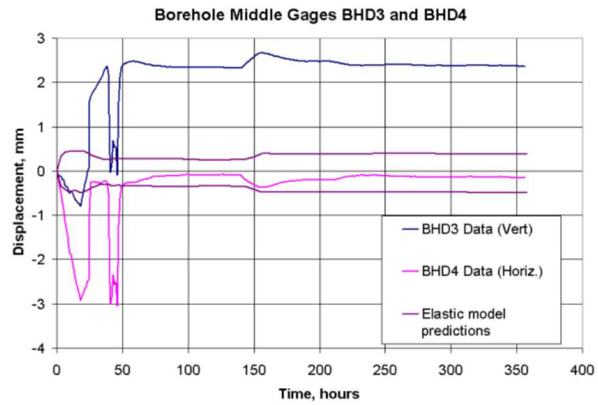


Figure 50. Thermal Expansion Measured at Borehole Gages BHD3 and BHD4

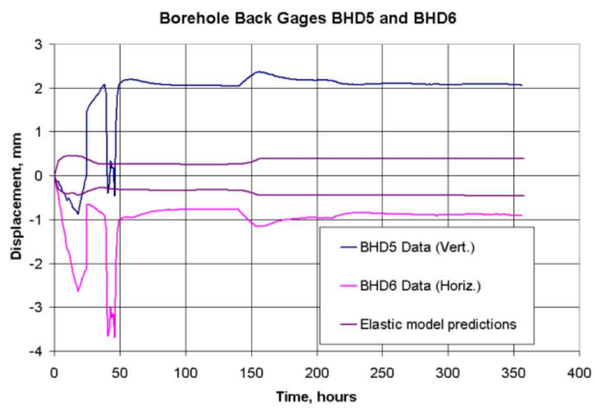


Figure 51. Thermal Expansion Measured at Borehole Gages BHD5 and BHD6 (DTN SN0212F4102102.003 for Figures 49-51)

Simulations were performed using JAS3D using a thermal expansion coefficient profile four times the magnitude as that obtained in the laboratory. Figures 52 and 53 compare the results with the larger values for α with the data and the original calculation for the middle and back borehole closure gages. The resulting predictions are closer to the data, but are still not in good agreement. It is highly unlikely that the measured thermal expansion coefficients are incorrect by a factor of 4; the measurement technique is well-developed and accurate, and the measured values agree well with other similar tuff samples from Yucca Mountain and elsewhere. These calculations were performed mainly to illustrate the significant magnitude of the discrepancy between the elastic model predictions and the measured field data.

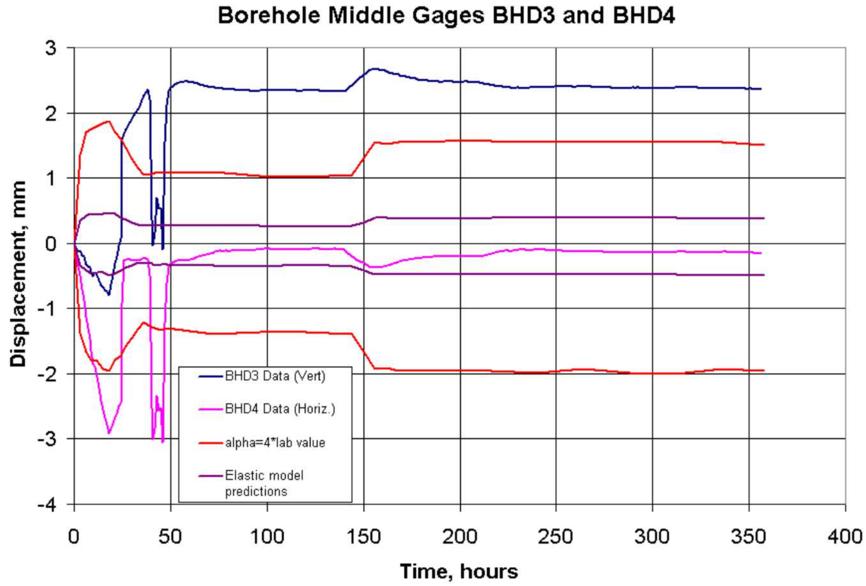


Figure 52. Thermal Expansion at Borehole Gages BHD3 and BHD4 with Thermal Expansion Coefficients Increased By a Factor or 4

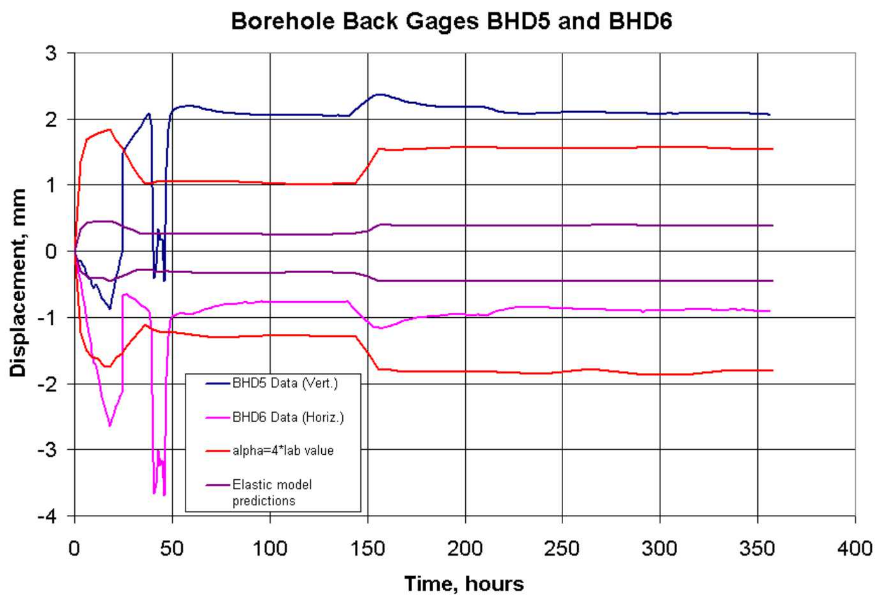


Figure 53. Thermal Expansion at Borehole Gages BHD5 and BHD6 with Thermal Expansion Coefficients Increased By a Factor or 4

The elastic model used for the preceding predictions assumes the rock mass to be intact. As a result, when the rock expands due to thermal input, there are two primary directions in which the rock will "go": toward the open drift, or toward the open boreholes and slots. However, the host rock is highly fractured, and the effects of such fractures are not captured by an elastic model. The Compliant Joint Model (CJM) is a material model programmed into JAS3D that does evaluate the effect of the presence of fractures. The CJM uses an equivalent continuum approach to model the behavior of jointed media. An equivalent continuum approach captures the average response of a jointed rock mass by distributing the response of the individual joints throughout the rock mass. The equivalent continuum model is described in detail in Blanford and Key (1991). The CJM in JAS3D can model up to four joint sets of arbitrary orientation. The fractures in each of these joint sets are assumed to be parallel and evenly spaced. The intact rock between joints is treated as an isotropic linear-elastic material. The CJM was first developed as a two-dimensional model (Chen, 1991), and analyses have been performed with this 2-D model for the G-Tunnel heated block test (Costin and Chen, 1991). Later, the CJM was extended to three dimensions for inclusion into JAS3D (Thorne, 1995).

The heating period for slot test #2 was modeled using the CJM. Two calculations were performed: the first included one horizontal joint set; the second contained two joint sets, a horizontal set and a set that was vertical and parallel to the borehole. It was thought that the existence of these sets would lessen the amount of rock displacement towards the open drift by providing a path of lesser resistance within the rock. The resulting predictions, as presented in Figures 54 and 55, seem to support this hypothesis. The closure displacements are closer to the data, and there is particularly good agreement with the data from the horizontal borehole gages throughout the entire heating period. This agreement is due to the presence of the vertical joint set, which allows more freedom of movement in the horizontal direction in which gages BHD4 and BHD6 are oriented. The calculations also indicate a smaller amount of rock displacement into the open drift. The results of the CJM calculations indicate that the evaluation of rock mass thermal expansion in an underground drift environment needs to include the effects of the presence of fractures.

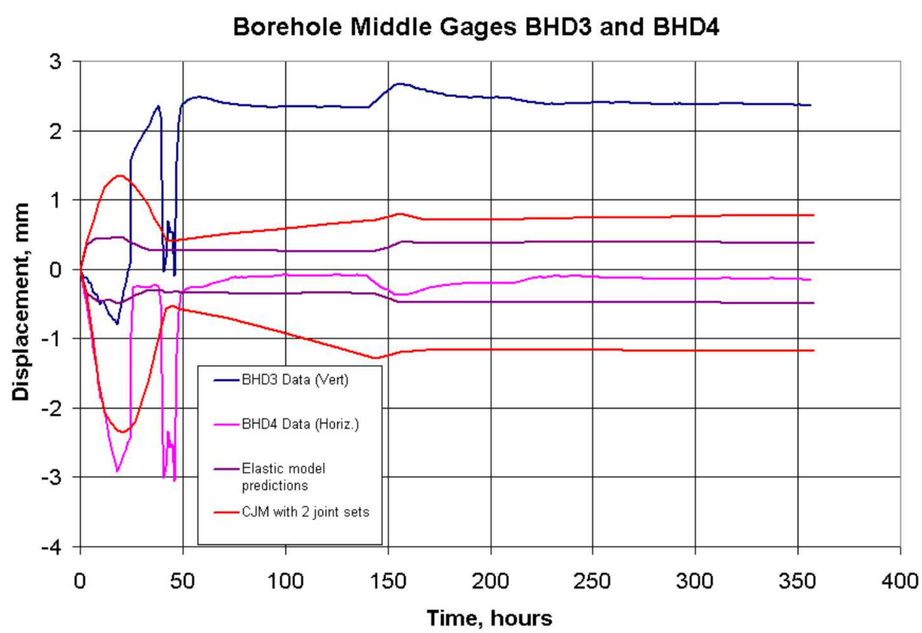


Figure 54. Thermal Expansion at Borehole Gages BHD3 and BHD4 Compared with Compliant Joint Model Calculations

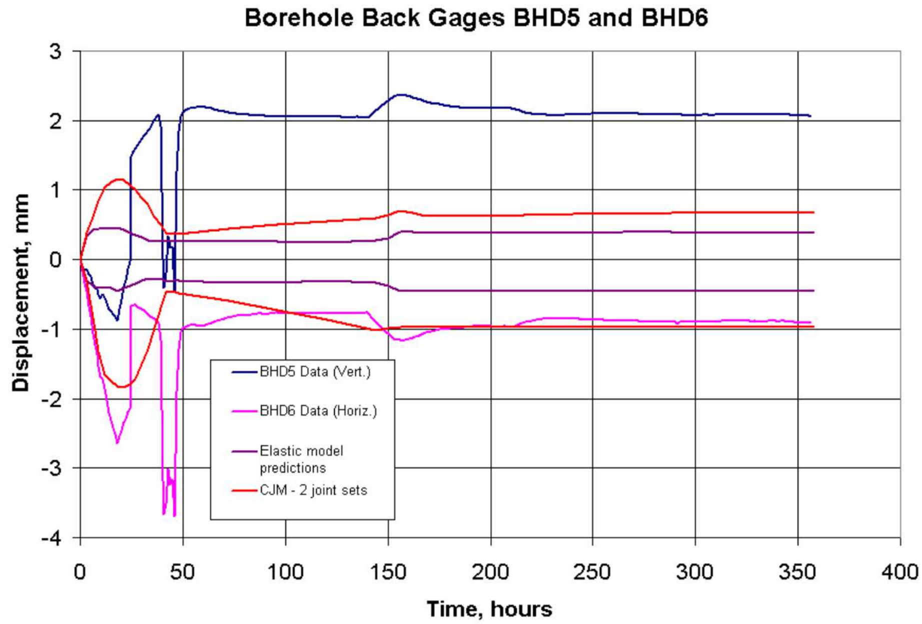


Figure 55. Thermal Expansion at Borehole Gages BHD5 and BHD6 Compared with Compliant Joint Model Calculations

7.2 ROCK FAILURE DURING HEATING AND PRESSURIZATION

For all three slot tests, rock failure was induced during the pressurization of the flatjacks. Rock spalling was observed in the boreholes for all three tests. Figure 56 shows the post-test condition of the borehole for Slot Test #1; the boreholes for the other two tests exhibited similar conditions. Rock failure also was observed at the drift surface for all three tests. Figure 57 shows a large movement of rock updrift of Slot Test #2, and Figure 58 shows rock failure between the slots and borehole of Slot Test #3. Rock failure was also noted during the heating phase for Slot Test #2; Figure 59 shows rock spalling in the borehole resulting from heating. For all these cases, it is evident that the in situ rock was at a stress state very near to its failure envelope before being further stressed, whether by thermal expansion or by pressurization. One desired result of these tests is to develop failure criteria for the Tptpul and Tptpll that can be implemented in the drift design process.

Figure 56. Damage within test borehole after Slot Test #1.

Figure 57. Rock damage near Slot Test #2.


Figure 58. Rock damage between slots and borehole from Slot Test #3.

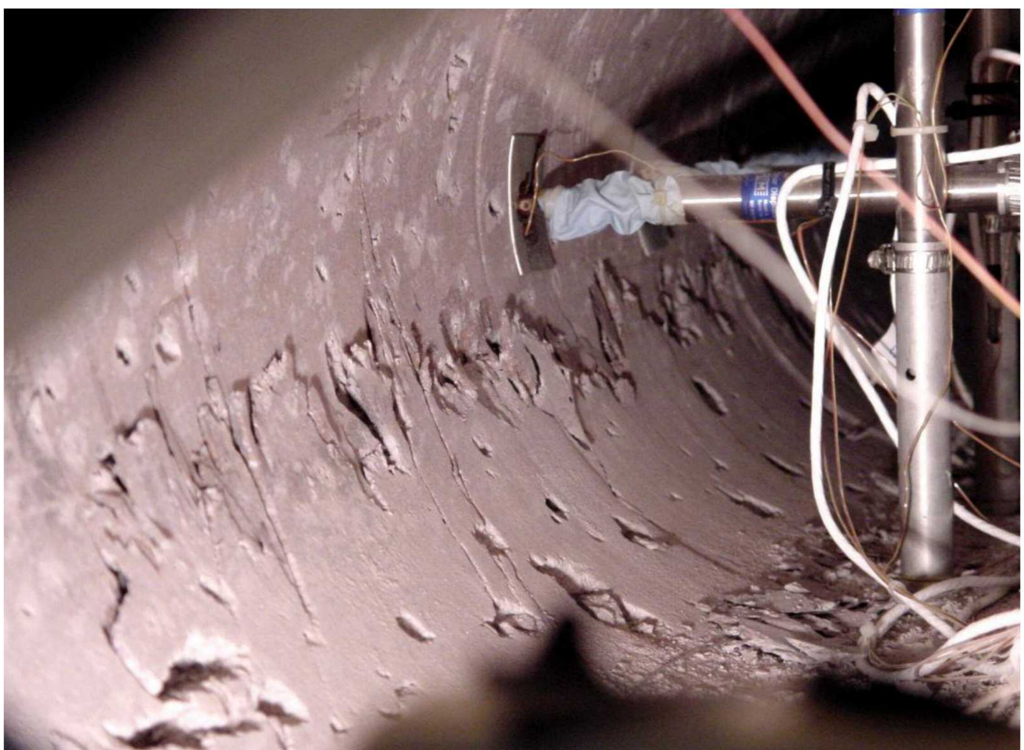
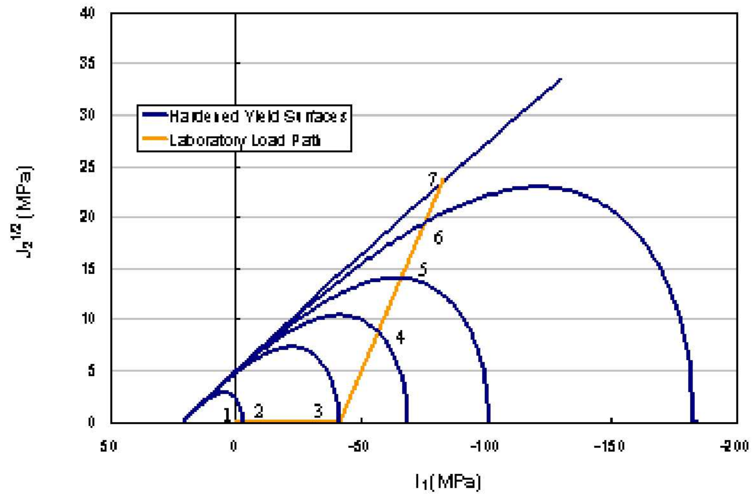


Figure 59. Thermally-induced spalling in the borehole during the heating phase of Slot Test #2.



1. Start of hydrostatic loading
2. First yield
3. End of hydrostatic loading and start of triaxial compression loading
4. Compactive deformation
5. Incompressible deformation
6. Dilatant deformation
7. Peak stress

Figure 60. Triaxial compression laboratory load path and the shape of the yield surface as it hardens during the test.

Typically, plasticity models describe separate yield surfaces to represent dilatant and compactive deformation individually. The dilatant deformation failure envelope is expressed by a shear failure equation, which can be linear or non-linear. The compactive deformation is expressed by a cap surface which moves due to hardening of the material. A more recent plasticity model, the isotropic geomaterial model (Fossum and Fredrich, 2000), is a continuous-surface plasticity model that describes compactive and dilatant deformation with a single yield surface. This allows microcracking and pore collapse to be represented, which are dilatant and compactive processes, respectively by a single yield surface. Figure 60 shows the yield surface as it hardens in the meridianal plane during a triaxial compression laboratory test. The ordinate in this figure, the square root of the second invariant, $J_2^{1/2}$, of the deviator stress, is proportional to the shear stress in the specimen while the abscissa, the first invariant of the Cauchy stress, I_1, is equal to 3 times the normal mean stress (compression negative). In a triaxial compression test the specimen is first loaded hydrostatically to a specified level and then this is followed by an increase in the magnitude of one of the principal stresses until the specimen fails or reaches a peak stress, while the other two principal stresses are held constant. This load path is shown in Figure 60. The hydrostatic portion of the test begins at the point labeled "1". From point 1 to point 2 the specimen deforms elastically, either linearly or non-linearly. Pore collapse initiates at point 2. From point 2 to point 3 the specimen compacts caused by continued elastic deformation and pore space depletion. At point 3 the magnitude of one of the principal stresses begins to increase while the other two are held fixed. The specimen begins to develop shear stresses that cause dilatant microcracking but macroscopically the specimen continues to compact. When the stress point is on the "compactive" side of the yield envelope, such as point 4, the inelastic volume strain is predominantly compactive, though there is some dilatant volume strain caused by microcracking. At point 5 the dilatant inelastic volume strain equals the inelastic compaction volume strain and the specimen is globally incompressible inelastically at this point. As the stress point proceeds to the "dilatant" side of the yield envelope, such as point 6, the inelastic volume strain is predominantly dilatant. At point 7 the specimen can no longer build up more stress and it either fails in shear, flows plastically, or strain softens.

As shown in Figure 60, the dilatant yield of a specimen asymptotes to a typical shear limit surface. Because of the combined effects of compaction, the shear limit surface is not always linear. The shear limit surface is given by

$$F_f(I_1) = J_2^{1/2} = \left(A_1 - A_3 e^{A_2 I_1}\right) - A_4 I_1$$

where $A_1 \ldots A_4$ are constants. Typically, these constants are developed from a series of triaxial compression tests at different confining pressures, all taken to rock failure. Because such a set of well-defined failure points does not exist for the pressurized slot tests, the shear envelope for the lithophysal rock are estimated from the JAS3D analyses used to derive the rock mass properties.

Figure 61 is a comparison of the square root of the second invariant, $J_2^{½}$, of the deviator stress to the first invariant of the Cauchy stress, I_1, for the heating phase of Slot Test #2. The stresses are calculated at locations around the borehole at a depth of 0.8 m from the drift surface. The stresses are based on the JAS3D calculations using the elastic model and the developed Tptpul parameters from Section 5. The angular location of each point is based on a counterclockwise rotation from the right horizontal axis of the borehole. The ±15-30° and ±150-165° locations correspond to the approximate locations in the borehole where spalling was observed in Figure 59. Note how the top and bottom of the borehole are predicted to be in tension during the heating phase. An approximate shear failure curve has been fitted to the calculated stresses based on the field observation that spalling occurred within a few hours after the onset of heating. The equation for the approximate shear failure curve for the Tptpul is given by (in MPa)

$$F_f(I_1) = J_2^{1/2} = \left(22 - 20e^{-0.02 I_1}\right).$$

A similar set of predictions for the heating phase using the compliant joint model calculations is shown in Figure 62. Note that when the presence of joints is included, the predicted tensile mean stress nearly disappears, whereas the shear stresses in the spalling locations increase. This relationship probably better describes the observed behavior in the borehole during heating. The estimated failure curve also shows that the in situ rock was already near or at failure conditions before the test began. This result is consistent with observations made at the test site.

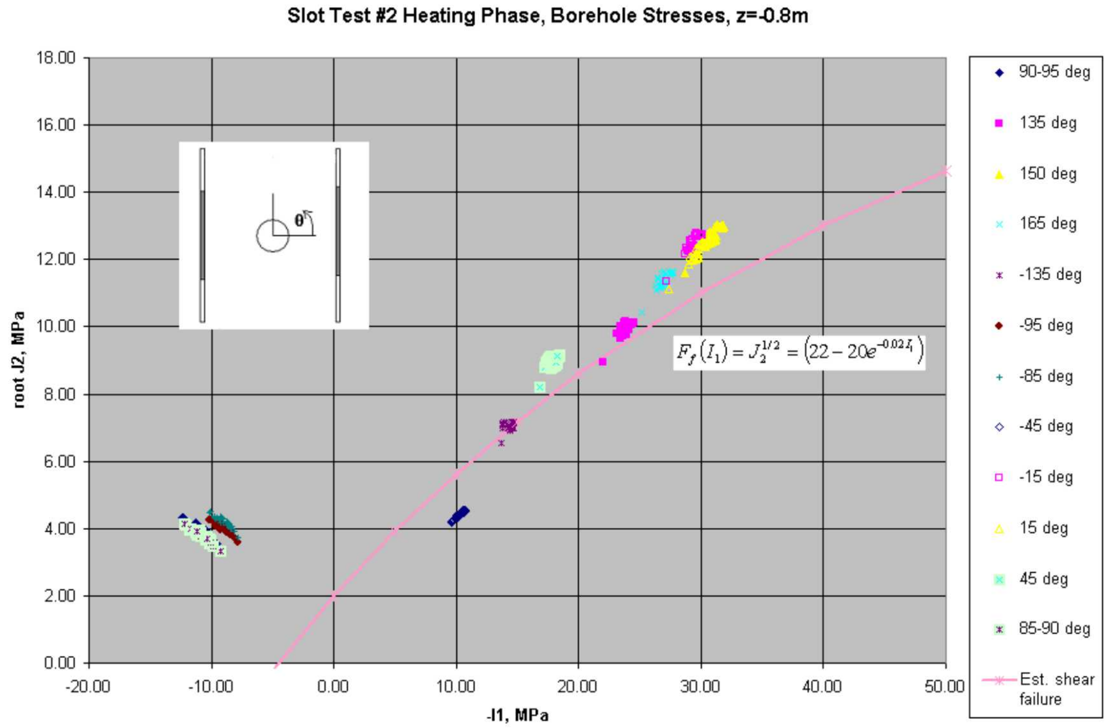


Figure 61. Predicted Shear Failure Envelope, Slot Test #2, Heating Phase, Elastic Model.

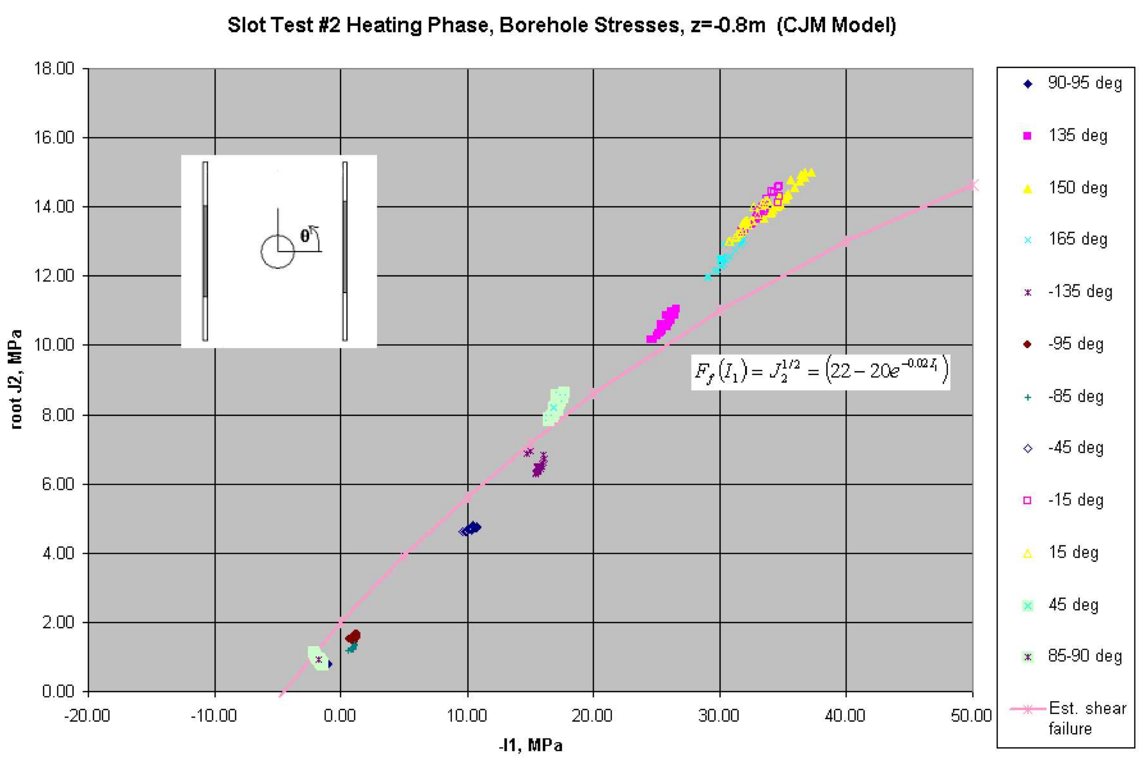


Figure 62. Predicted Shear Failure Envelope, Slot Test #2, Heating Phase, CJM Model.

The same shear failure envelope should apply to the Tptpul host rock during the pressurization phase of Slot Test #2. Figure 63 plots the I_1-$J_2^{1/2}$ relationship for the same borehole locations, using the elastic model calculations. Of particular interest here is the movement into the failure regime of other circumferential locations around the borehole. Such failures were observed during the test.

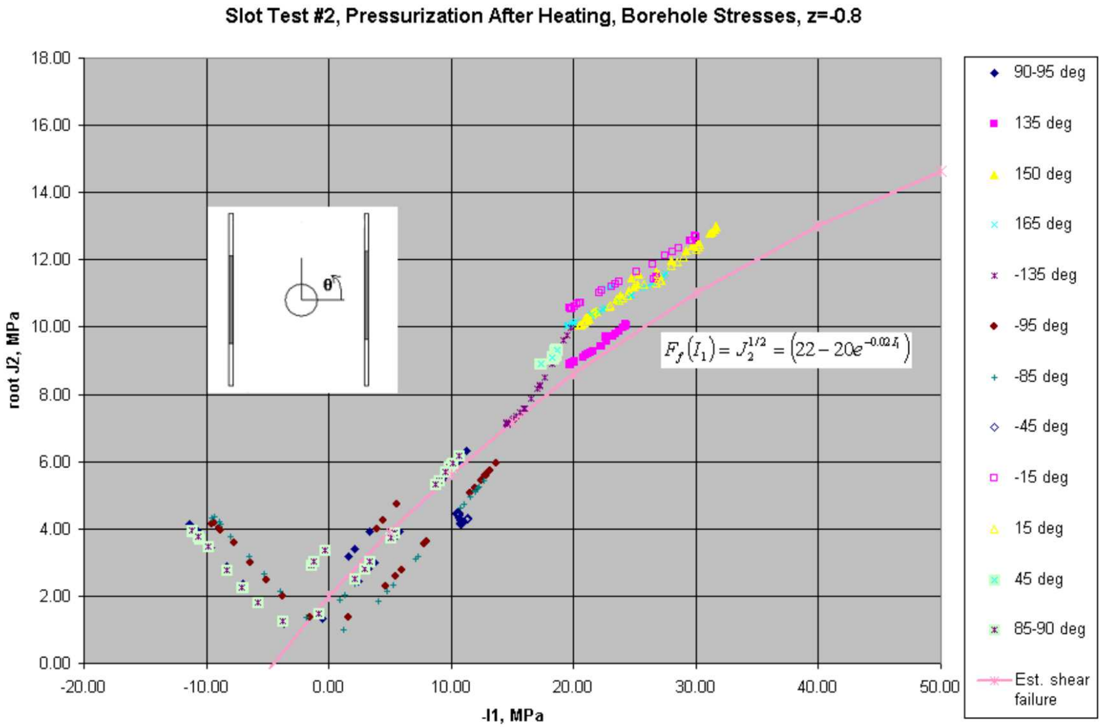


Figure 63. Predicted Shear Failure Envelope, Slot Test #2, Pressurization Phase, Elastic Model.

A similar failure envelope can be estimated for the Tptpll host rock tested for Slot Test #3. As shown in Figure 58, rock cracking was observed at the drift surface during pressurization along lines at approximately 45° with respect to the test coordinate axes. Figure 64 shows predicted areas of high shear stress emanating from the borehole during the instant peak pressure. The cutaway view in Figure 64 is on a plane at 1.1m from the top of the borehole, at approximately the center of the flatjacks. Figure 65 shows a comparison of I_1-$J_2^{1/2}$ for points in this plane starting at the borehole and extending toward the "bottom" of the left slot. Shear failure occurs first at the borehole surface and extends toward the slots. Failure also occurs vertically, i.e., up toward the floor of the drift, as the cracks propagate with increasing pressure. From a comparison of predicted stresses with observed failure, the Tptpll rock appears to be weaker than the Tptpul. An estimated shear failure envelope for Slot Test #3 is:

$$F_f(I_1) = J_2^{1/2} = (13.5 - 12e^{-0.015I_1}).$$

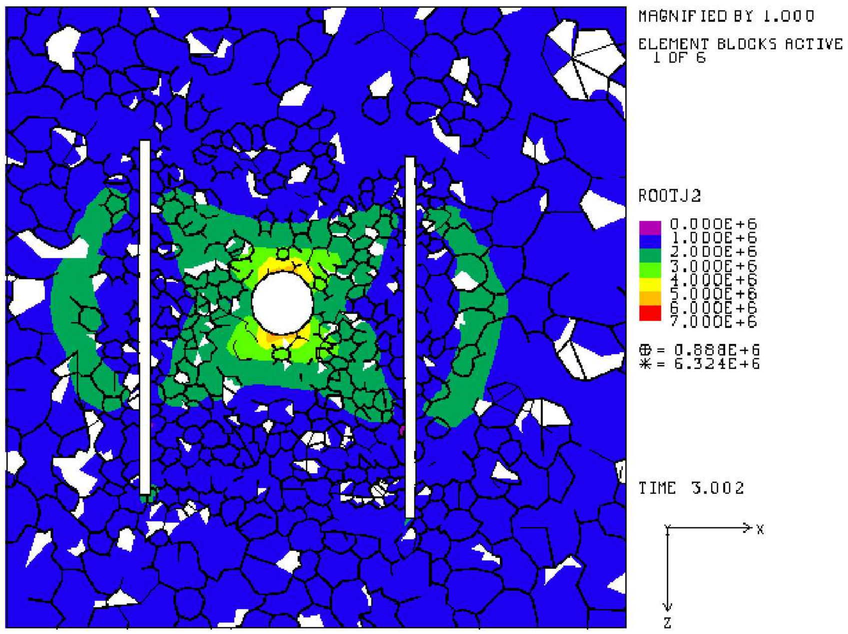


Figure 64. Predicted deviatoric shear stress during Slot Test #3, 1.1m from top of borehole.

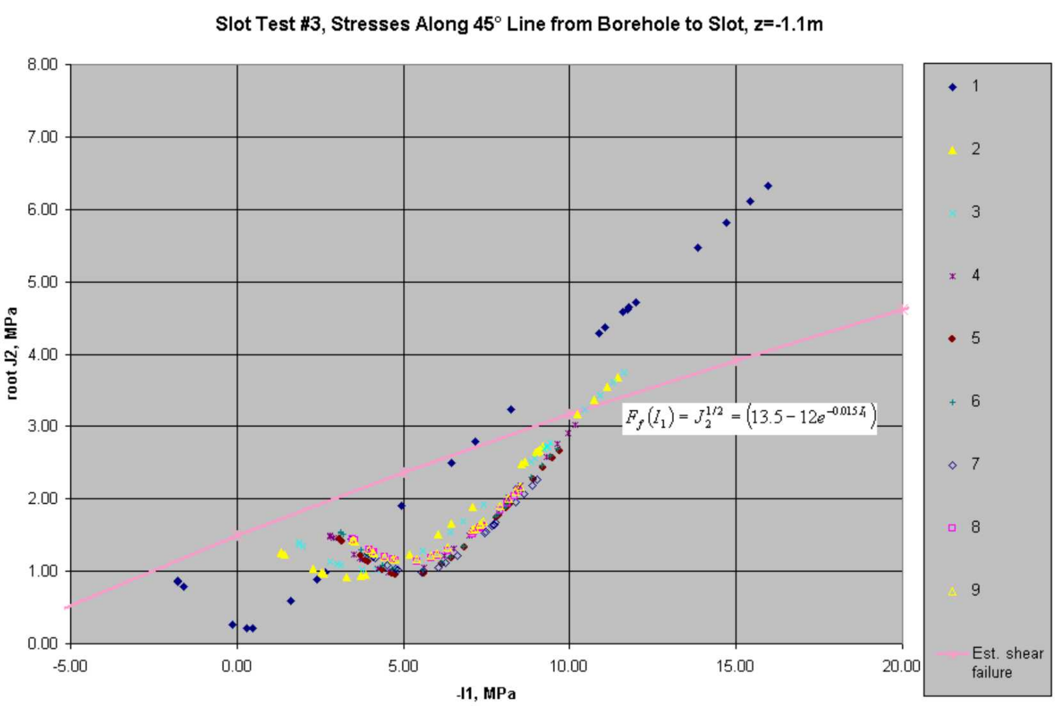


Figure 65. Predicted Shear Failure Envelope, Slot Test #3, Elastic Model.

8. CONCLUSIONS

Sandia National Laboratories have developed an in situ pressurized slot testing technique for the field measurement of bulk thermal-mechanical properties. A series of three tests were conducted in the welded tuffs of Yucca Mountain, Nevada. The pressurized slot testing described in this report has provided thermal-mechanical properties of the Tptpll lithostratigraphic unit, which is characterized by lithophysae which range in size from centimeters to meters. The field data obtained from the series of tests, used in conjunction with thermal-mechanical numerical modeling techniques, can be used to develop a suite of bulk thermal-mechanical rock properties (thermal expansion, rock mass modulus, compressive strength, time-dependent deformation) over a range of temperature and rock conditions for a given stratigraphic unit.

Rock mass values of elastic modulus and Poisson's ratio were obtained at three test locations. The ambient values of elastic modulus ranged from 0.5-10. GPa in the lower lithophysal layer, and 3.0 GPa in the upper lithophysal layer. A reduced value of 1.5 GPa was observed in the upper lithophysal layer at a nominal temperature of approximately 90°C. The reduced rock mass modulus at the higher temperature indicates that some rock failure occurred during the heating process, which created fractures and deformed existing lithophysae and pore space to allow greater displacement during pressurization. In addition, a comparison of test data with results from numerical analyses utilizing a compliant joint model indicate that the predicted rock mass behavior is highly influenced by the presence of fractures in the rock. This discrepancy between predicted elastic behavior and the behavior described by the test data is most pronounced in the prediction of thermal expansion of the host rock. The compliant joint model analyses indicate that the presence of fractures provide alternate paths for rock expansion, resulting in significant discrepancies in the prediction of displacements within the boreholes.

A shear failure analysis using the test data indicate that the host rock for the three slot tests were near the failure envelope even before the initiation of the tests, and that thermal expansion and pressurization both caused visible rock failure. Shear failure envelopes were estimated based on test data and observed cracking during the tests. Such failure envelopes can be used for design purposes to evaluate thermal and mechanical loading conditions in radioactive waste repository environments, and indicate possible drift design options to provide long-term drift stability and minimization of crack propagation.

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